ERDC/CERL TR-00-18

Construction Engineering Research Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Performance Testing of Fiber-Reinforced Polymer Composite Overlays for Seismic Rehabilitation of Unreinforced Masonry Walls

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June 2000

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Foreword

This study was conducted for the Military Programs Office, Headquarters, U.S. Army Corps of Engineers, under Project 4A162784AT41, "Military Facilities Engineering Technology"; Work Unit FL-003, "Seismic Rehabilitation of Masonry Walls." The Technical Monitor was Charles H. Gutberlet, CEMP-ED.

The work was performed by the Materials and Structures Branch (CF-M) of the Facilities Division (CF), U.S. Army Construction Engineering Research Laboratory (CERL). The CERL Principal Investigator was Orange S. Marshall, Jr. The technical editor was Gordon L. Cohen, Information Technology Laboratory – CERL. Mark W. Slaughter is Acting Chief, CEERD-CF-M, and L. Michael Golish is Chief, CEERD-CF. Dr. Paul A. Howdyshell is Acting Technical Director of the Facility Acquisition and Reinvention Business Area. The Acting Director of CERL is Dr. Alan W. Moore.

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1 Introduction

Background

The U.S. Army owns approximately 143,000 buildings within the Continental United States. The dominant structural system in this inventory is masonry — either brick or concrete block. Many of these structures are either unreinforced or only lightly reinforced. In the wake of past earthquakes it has been seen that unreinforced and lightly reinforced masonry structures perform very poorly during seismic events. This poor structural performance not only endangers personnel, but it also can interrupt mission-critical activity.

In anticipation of Federal requirements for seismic strengthening of structures, the U.S. Army Construction Engineering Research Laboratory (CERL) is investigating applications of fiber-reinforced polymer (FRP) composites for seismic strengthening of unreinforced masonry (URM) walls. The phase of research reported here addresses the use of FRP materials systems externally applied to a single masonry wall surface.

Objectives

This objective of this research program is to develop procedures for rehabilitating or structurally upgrading unreinforced masonry walls using various advanced composite materials systems that are now commercially available. The final product of this multi-year work package will be published design specifications and construction guidance for use by the Army and suitable for transfer to other military and civilian agencies as well as the U.S. construction industry.

The objectives of the current phase of this research were to:

1. quantify the structural properties of masonry wall test sections and samples that have been structurally strengthened with FRP composite materials systems
2. characterize the ability of these composite systems to hold together test specimens after the joints and/or masonry units have cracked through progressive application of heavy loads.

Approach

Twenty CMU walls and twenty brick walls with no internal reinforcing were constructed. Mortar cubes and standard masonry prisms were simultaneously constructed to evaluate the strength of the mortar used in the constructions. In addition, a series of triplets were constructed. A variety of FRP composite systems were applied to the masonry constructions, and testing was conducted on the walls, prisms, and triplets to evaluate the capability of FRP composite systems to strengthen unreinforced masonry.

Scope

This phase of the investigation comprised a feasibility study to determine the capability of various FRP composite systems to strengthen masonry test specimens and to maintain the specimens' structural integrity upon failure. Because this was a feasibility study, application costs were not considered as an evaluative criterion in performance assessments.

Mode of Technology Transfer

The results of this study will be incorporated into subsequent phases of this research program. Upon completion of the program, design guidance and construction specifications will be drafted for publication in a Corps of Engineers Technical Instruction, Engineer Technical Letter, or other military criteria documents.

Applicable findings of this research program also will be submitted for incorporation into the FEMA* 273 and other appropriate model building code documents. Findings will be presented to the engineering community in Army Corps of Engineers Structural Engineering Workshops and at professional technical conferences.

* FEMA: Federal Emergency Management Agency.

Units of Weight and Measure

U.S. standard units of measure are used throughout this report. A table of equivalencies for the International System of Units (SI) is provided below.

SI conversion factors		
1 in.	=	2.54 cm
1 ft	=	0.305 m
1 oz/sq yd	=	33.906 g/m^2
1 sq in.	=	6.452 cm^2
1 sq ft	=	0.093 m^2
1 oz	=	28.35 g
1 lb	=	0.453 kg
1 kip	=	453 kg
1 psi	=	6.89 kPa
°F	=	(°C x 1.8) + 32

2 Description of Materials and Testing Program

General Properties of Composites

A composite is a combination of two or more materials into a single system that exhibits combined properties of its individual components. The system constituents retain their distinct identities (they do not dissolve or merge completely into each other) and act in concert as a hybrid to provide new, desirable properties. Reinforced concrete, for example, is a composite consisting of steel reinforcement, sand and gravel fillers, and a portland cement matrix.

Fiber-reinforced polymer (FRP) composites consist primarily of a reinforcement material such as glass, carbon, or aramid fibers bound in a polymer matrix. Fillers also may be added to modify the composite's physical, mechanical, thermal, electrical, or other properties, or to lower material cost or density. The polymer matrix may be a thermoplastic or a thermoset. A thermoplastic polymer (e.g., polyethylene, polyvinyl chloride, or polystyrene) is a polymer capable of being repeatedly softened by an increase of temperature and hardened by a decrease in temperature. A thermoset polymer (e.g., epoxy, polyester, and polyurethane) is a polymer that cannot be softened and reformed by an increase in temperature. When the polymer forms, chemical crosslinking between polymer chains occurs and the cured polymer cannot be returned to a molten state.

The primary load-bearing component of an FRP composite is its fibrous reinforcement. The matrix serves to hold the fibers in place and transfers loads within the member from one fiber to another. Depending on the composite specifications, additives, fillers, or coatings may also be incorporated in the composite to protect against attacks by ultraviolet (UV) radiation, fire, moisture, chemicals, and/or fire resistance.

Because FRP composites have not existed long, the civil engineering community is only gradually beginning to explore these materials as an economical, effective alternative to steel and reinforced concrete. As used in civil engineering applications, the most common FRP composites have been E-glass, carbon, and/or aramid fiber reinforcement in a polyester, vinyl ester, or epoxy matrix. An important reason these polymers are used is because they cure by chemical reaction at ambient temperature.

Test Specimens

Wall Panels

Twenty 4 x 4 ft concrete masonry unit (CMU) wall panels (Figure 1*) and twenty 4 x 4 ft double-wythe brick wall panels (Figure 2) were constructed, as well as prisms and triplet test specimens that are described later in this chapter. Four different FRP composite systems were used: glass epoxy, carbon epoxy, glass vinyl ester, and adhesively bonded glass-epoxy grid. Each FRP system was applied to one face of four CMU wall panels and four brick wall panels. Four unaltered CMU panels and four brick panels were used as controls. The reinforcing fiber orientation used for all of these wall panels was 0/90 degrees to the mortar joints.

The brick test specimens were constructed using standard 10-hole red clay bricks. The CMU specimens were constructed using standard 8 x 8 x 16 in. blocks.

Type N mortar was used for all wall, prism, and triplet construction. The mortar mix was 1 part (by volume) type III portland cement, 0.5 parts lime, and 4.5 parts sand. Water was added as necessary to keep the mortar workable. Mortar cubes were prepared from each mortar batch used. All mortar joints were 3/8 in. wide.

The *glass-epoxy FRP* composite system consisted of two layers of 8.4 oz/sq yd E-glass reinforcement with a balanced modified crowfoot weave and an amine-cured biphenyl-A epoxy resin. The surface to receive the FRP system was wetted with the epoxy using a paint roller. The reinforcing glass fabric was saturated with the epoxy and hand-laid on the surface. After the first layer of fabric was placed and air bubbles pressed out using hand pressure, the second layer was applied. Care was taken to maintain the 0-degree/90-degree fiber alignment

* All figures are presented at the end of the main text, immediately preceding Appendix A.

noted previously. Because of the porosity of the CMU walls, it was observed that the CMU was wicking epoxy out of the FRP and drying the glass fabric. To prevent this drying, a batch of epoxy resin thickened by a thixotrope filler was mixed and rolled onto the surface of the FRP that had been applied to the four CMU walls.

The *glass-vinyl ester FRP* system used the same layers of 8.4 oz/sq yd E-glass reinforcement as the glass-epoxy system with a moisture-cured urethane primer for the walls and a methyl-ethyl-ketone peroxide-cured vinyl ester resin for the FRP. Rather than wetting the wall surfaces first with the vinyl ester resin, the wall surfaces were wetted using the urethane primer; the saturated fabric was applied once the primer was partially cured.

The *carbon-epoxy FRP* system consisted of one layer of 5.7 oz/sq yd plain weave carbon fabric and the amine-cured biphenyl-A epoxy resin used in the glass-epoxy system. The application procedure was also the same as used for the glass-epoxy system.

The *glass-epoxy grid* system consisted of a prefabricated and cured grid made of E-glass and a biphenyl-A epoxy resin. The grid was 12.45 oz/sq yd with five tows (strands) per inch in the warp direction and four in the fill (Figure 3). The grid was fastened to the wall using a filled epoxy adhesive system. The adhesive was trowelled onto the wall surface and the grid was pressed into the adhesive using metal rollers. Two layers of grid were used. The first layer was pressed into the adhesive with the warp in a vertical direction. After it was pressed into the adhesive, more adhesive was trowelled onto the wall and a second layer of fabric was pressed into it with the fill in the horizontal direction. The surface of the adhesive was then trowelled to provide a smooth finish.

Masonry Prisms

Thirty masonry prisms were constructed; half were a 3-CMU-block stack (Figure 4) and the other half were a 5-brick-high stack (Figure 5). Each FRP system was applied to one face of three of each type of prism. The reinforcing fiber orientation used for all of these wall panels was 0/90 degrees to the mortar joints. Three CMU and three brick prisms were used as controls.

Masonry Triplets

Fifty-one brick triplets were also constructed, consisting of three bricks stacked so that the center brick was offset approximately ½ in. (Figure 6). Six triplets were used as controls with no FRP applied to them. Strips of the glass-epoxy system, one fabric-layer thick and oriented at 0/90 degrees to the mortar joints, were applied to two sides of the triplets with the FRP width varying from 1 in. to 6 in. at 1 in. increments. The same was done using the carbon-epoxy system. Two- and three-layer thicknesses of 6 in. wide glass-epoxy strips and two layers of 6 in. wide carbon-epoxy strips were also applied. Table 1 lists all triplet configurations used in testing.

Table 1. Triplet configurations.

Width of FRP (in.)	FRP Type	Number of Reinforcing Plies
0	N/A	N/A
1	Glass-Epoxy	1
1	Carbon-Epoxy	1
2	Glass-Epoxy	1
2	Carbon-Epoxy	1
3	Glass-Epoxy	1
3	Carbon-Epoxy	1
4	Glass-Epoxy	1
4	Carbon-Epoxy	1
5	Glass-Epoxy	1
5	Carbon-Epoxy	1
6	Glass-Epoxy	1
6	Carbon-Epoxy	1
6	Glass-Epoxy	2
6	Carbon-Epoxy	2
6	Glass-Epoxy	3

In addition to the walls, prisms, and triplets, mortar cubes were made and tested from every mortar batch used in test specimens. The specific mortar for each specimen was tracked to identify changes in test specimens as a result of different mortar properties (Appendix C).

Test Procedures

The 4 x 4 ft wall panels were tested in accordance with ASTM E 519-81 (reapproved 1993), *Standard Test Methods for Diagonal Tension (Shear) in Masonry Assemblages*. Testing was conducted in CERL's million-pound load test machine. The mortar cubes were tested according to ASTM C 109-98, *Test Method for Compressive Strength of Hydraulic Cement Mortars*. The test consisted of applying a compressive load at a rate of 100 psi per second to a cube until it failed.

The prisms were tested according to ASTM C 1314-97, *Test Method for Constructing and Testing Masonry Prisms Used to Determine Compliance with Specified Compressive Strength of Masonry*.

The triplet tests were a non-standard test designed to evaluate the shear strength of a masonry specimen across the mortar joint. This test consisted of applying a compressive load at a rate of 2 kips/min on the center offset brick, which created shear in the mortar joints on either side. Testing was conducted using a United Testing Machine (United Calibration Corp., Garden Grove, CA) with a 10 kip capacity. When the capacity of the United machine was reached, the final tests were conducted on the million-pound test machine.

3 Test Results

Wall Tests

The diagonal tension tests did not demonstrate any statistically significant increase in strength attributable to the composite overlays, but significant changes in the failure behavior were observed. Figures 7 and 8 show the average failure loads versus the overlay type for CMU and brick, respectively. Some increase in the area under the load-deflection curve was seen in some of the walls. Figure 9 shows the load/deflection curves for the CMU control specimens and Figure 10 shows those for the brick control specimens. These curves show typical brittle behavior with little ductility. Figures 11 – 14 show load/deflection curves for the different overlays on CMU walls, and Figures 15 – 18 show load/deflection curves for the brick wall panels. These show an increase in the area under the load/deflection curve relative to the controls, indicating that the wall was able to sustain loads at a higher displacement with the composite overlays than were the control specimens. This ability to sustain load beyond peak load is significant in that it represents *pseudo ductility* in the system. Ductility is the ability of a material to deform plastically before fracturing. A pseudo ductile materials system behaves as if it were ductile even though individual components of the system may fail in a brittle manner. In these tests, the masonry typically failed but the FRP was able to sustain a load beyond that failure point. Appendix A shows the data for all wall section tests.

The control specimen failures were all sudden and brittle — either bed joint sliding or stair step fracture along mortar joints. Walls upgraded with FRP generally showed a different failure mechanism: cracking would initiate at one loading shoe and progress across the specimen to the other shoe. Generally, crack growth would progress slowly to a point, then suddenly progress to completion. Appendix B contains drawings of the wall crack patterns documented in these tests. The FRP overlay materials adhered very well to the masonry and held the wall pieces together after failure. This failure behavior is also significant in that the FRP overlay prevents masonry units and wall sections from becoming disassociated from the structure and falling. Because this type of falling hazard often causes injury or death when URM structures fail, it can reasonably be inferred that composite overlays may help to reduce casualties even when a masonry structure fails during an earthquake.

Prism Tests

No strengthening was observed in the CMU prism tests as a result of the composite overlays (Figure 19), primarily due to the failure mechanism of the masonry units themselves. Failure always initiated by fracture of the cross webs, allowing the two faces of the CMUs to separate. This is the typical failure mode for block masonry prisms. Average f'm values for the control, glass-epoxy, glass-vinyl ester, carbon-epoxy, and glass grid-epoxy systems were 2362, 2257, 2241, 2178, and 2201 psi, respectively.

Some strengthening was observed in the brick prism specimens, however (Figure 20). The typical failure mode in a brick prism is splitting along the short dimension of the specimen, along the face where the composite was applied. In this case, the composite was applied to the critical section of the specimen, so it was more likely to have a positive effect on strength. Average f'm values for the control, glass-epoxy, glass-vinyl ester, carbon-epoxy, and glass grid-epoxy systems were 2164, 2976, 3130, 2738, and 2700 psi, respectively. The glass-vinyl ester system provided the highest increase in strength at 45 percent, while the glass grid-epoxy system provided the lowest with a 25 percent increase in strength. Appendix D shows the prism test data for all tests.

Triplet Tests

The brick triplet tests evaluate shear bond strength across the mortar joints and the ability of FRP composites to strengthen that shear bond. As the width of the FRP composite on the specimen increased, so did the triplet strength. The average failure load of the control specimens was 2.28 kips. One 6 in. wide glass-epoxy specimen exceeded the 10 kip capacity of the test machine, as did a 4 in. wide carbon-epoxy specimen. The strength increase was fairly linear in proportion to the increase in FRP width. Figure 21 shows the glass-epoxy triplet test results and Figure 22 shows the results for the carbon-epoxy system. Appendix E shows the data for all triplet tests.

4 Discussion of Results

Wall Tests

The results of the diagonal shear testing of the 4 x 4 ft wall sections were mixed. No significant change in ultimate strength was observed as a result of the composite overlays. Some change in behavior, however, can be seen in the post peak load behavior of the specimens. In the control specimens, the failure was sudden and resulted in total collapse of the specimen. In some test specimens, however, the composite overlay apparently helped to prevent a total masonry collapse. The composite appears to have helped hold some fractured wall chunks together, thereby preventing masonry units and wall segments from falling away. This benefit is significant from a life-safety standpoint in that it reduces the hazards associated with masonry failure. It is also significant in that the failed wall maintains some residual load carrying capacity.

According to *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (FEMA 273), the ability to sustain load after peak load can result in greater m factors, and these may reduce the seismic demand or forces used in design. In URM life-safety design, the m factors, component, or element demand modifiers used to account for expected ductility associated with the expected action at a given performance level are 3 for bed joint sliding and $3h_{eff}/L > 1.5$ for pier rocking behavior. In comparison, values for reinforced masonry shear walls can be as high as 7 for life-safety design. Under this design philosophy, applying composite overlays to raise the m factor of URM walls from 3 to 6, for example, the effective earthquake resistance of the wall can double without actually increasing the strength of the masonry itself.

Even with the observations on wall performance in these diagonal tension tests, it is evident from test results and failure patterns that the failures did not accurately represent actual wall behavior. Failures initiated at the loading points and cracks often propagated along the edge of the specimen, splitting it through its thickness. It became evident that uniform stress distribution was not possible using the current test methodology. Consequently, an alternative shear panel test was developed for future testing.

Prism Tests

CMU and brick prism testing was conducted as a control procedure to monitor material properties throughout the testing program. No improvement was anticipated in compression test results for prisms with composite overlays, but a complete test series of all combinations of masonry units and composite systems was performed, as well as controls.

As predicted, the CMU prisms showed no increase in strength, but there was a 20 – 45 percent strength increase for the brick masonry prisms compared to the control specimens. Two possible explanations are offered. First, masonry prism strength is significantly affected by the strength of the mortar. Approximately 3 months passed between testing of the control specimens and the overlay specimens. The controls were tested 31 days after construction. The glass-epoxy, glass-vinyl ester, and carbon-epoxy prisms all were tested 120 days after construction, and the glass grid-epoxy prisms were tested 162 days after construction. While it is possible that this time lapse may account for some disparity in the strength results, a strength increase of 25 percent or more beyond the 28 day standard cure time would be extreme. Furthermore, the composite specimen with the lowest average strength was tested after the longest cure time, and this also suggests other factors were affecting prism strength.

The failure mode of a brick prism is different than for a CMU block prism. An ungrouted (hollow) block prism tends to split longitudinally, fracturing through the cross webs. A solid brick prism tends to split transversely, through the face of the brick. It is evident from the test data that the composite overlay had a significant effect on the prism strength.

Triplet Tests

The triplet test was designed to evaluate the in-plane shear resistance of a masonry specimen across a mortar joint. Several variations of the triplet test have been developed by researchers, but to date it is a non-standard test. The test is intended to provide relative quantitative values on the ability of a composite overlay to resist bed joint sliding under in-plane shear. The results of the triplet tests showed significant strengthening with both increased width and thickness of the composite reinforcement material. Some form of simple test of this type may be feasible to use as a quality assurance measure in the future, much as concrete cylinder tests are now used (i.e., to determine the strength of in-place concrete to meet or exceed construction specification requirements).

5 Conclusions

Externally applied FRP composite materials show potential for seismic rehabilitation of URM walls. The testing program documented here demonstrates that FRP composite materials can minimize the disintegration of unreinforced masonry walls that are loaded to failure. The FRP materials adhered very well to both the CMU and brick test specimens, and when the specimen failed, the composite overlays successfully held fractured wall sections together.

During the course of testing it became clear to the researchers that the diagonal shear test — while an accepted standard — is not well suited for determining the effects of composite overlays on URM walls. This test produces a non-uniform stress distribution in the specimens, and the loads applied to the specimens are not representative of in-service conditions. Additionally, it was observed that the specimen failures were more a function of the test setup than the failure modes of the specimens themselves. The nature of the failure mechanism observed in these tests indicates that the diagonal shear test does not accurately represent conditions important in assessing the performance of shear walls. Therefore, the researchers will switch to a racking test in future investigations. It is believed that a racking test will much more closely represent the stresses placed on real-world walls in service during a seismic event. As this type of test produces more relevant quantitative data, the researchers will better be able to measure the reinforcement effects of various composite overlay materials and application schemes.

In some cases the test results indicate that FRP composite overlays can strengthen masonry prisms. The FRP overlays generally stayed bonded to the masonry substrates throughout the tests; when the failure mode was a fracture of the surface bonded to the composite material, strengthening was observed compared to the control specimens.

The triplet tests showed that FRP composite overlays can strengthen the brick/mortar joint, and that strengthening increases at an approximately linear rate as a function of the FRP overlay width. The testing equipment available for these investigations did not permit a study of joint strengthening as a function of FRP overlay thickness.

In all tests, whenever the composite was applied directly to a failure surface, an improvement was observed in the total strength of the specimen. Furthermore, by holding the diagonal tension specimens together, the composite systems enabled a pseudo ductile response during wall failure. If such pseudo ductile behavior could be guaranteed through appropriate material and application specifications, improved safety factors could theoretically be achieved without necessarily having to increase peak load. Also, because composite overlays can hold together the fragments of a failed wall, a reduction in falling hazards may be achieved; this would mitigate a cause of injury that has been common when URM walls fail during earthquakes.

Overall, this testing program has demonstrated that FRP composite overlays have excellent potential for improving URM structural performance during an earthquake.

Figures

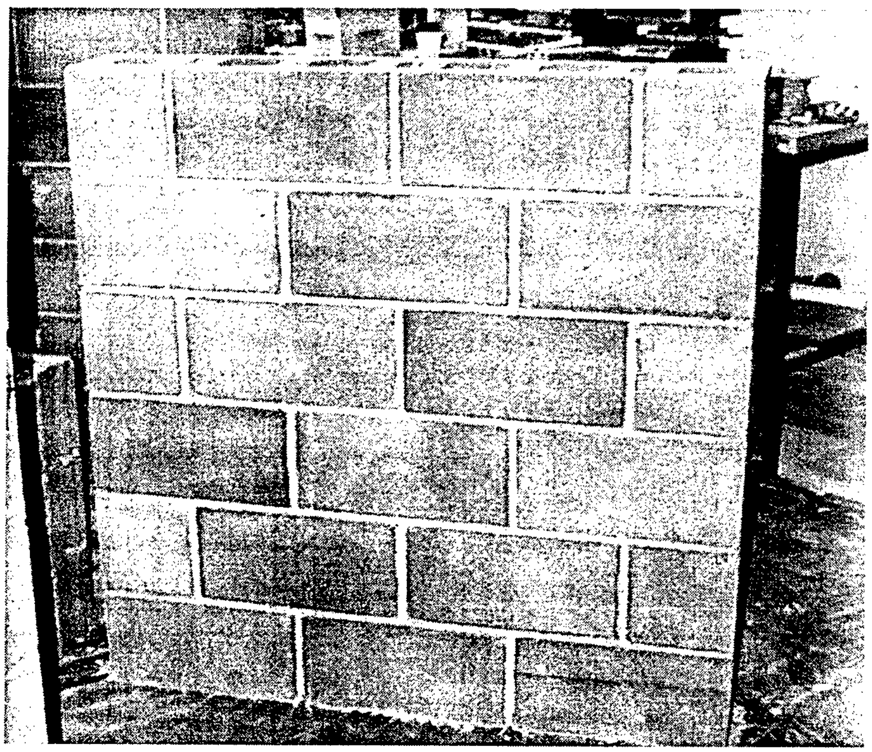

Figure 1. CMU wall panel (4 x 4 ft).

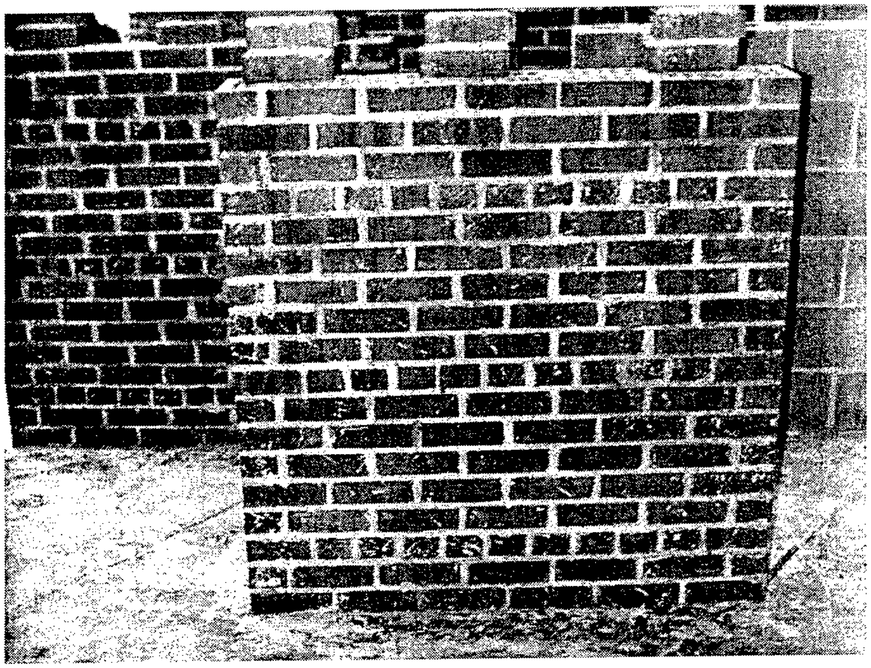

Figure 2. Brick wall panel (4 x 4 ft).

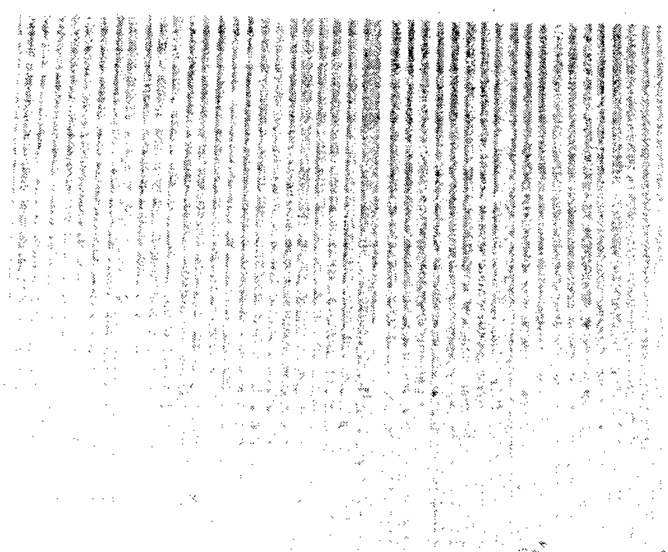

Figure 3. Glass-epoxy grid.

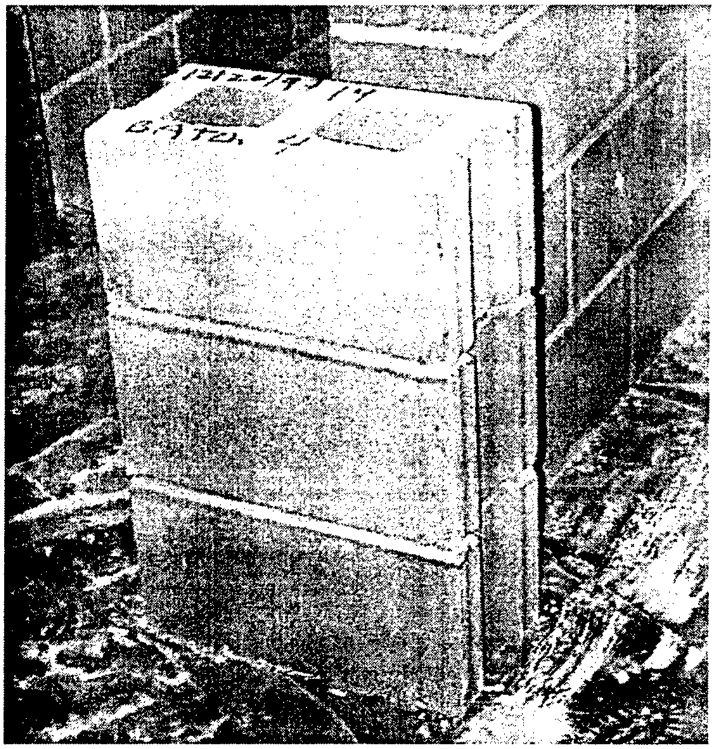

Figure 4. CMU prism.

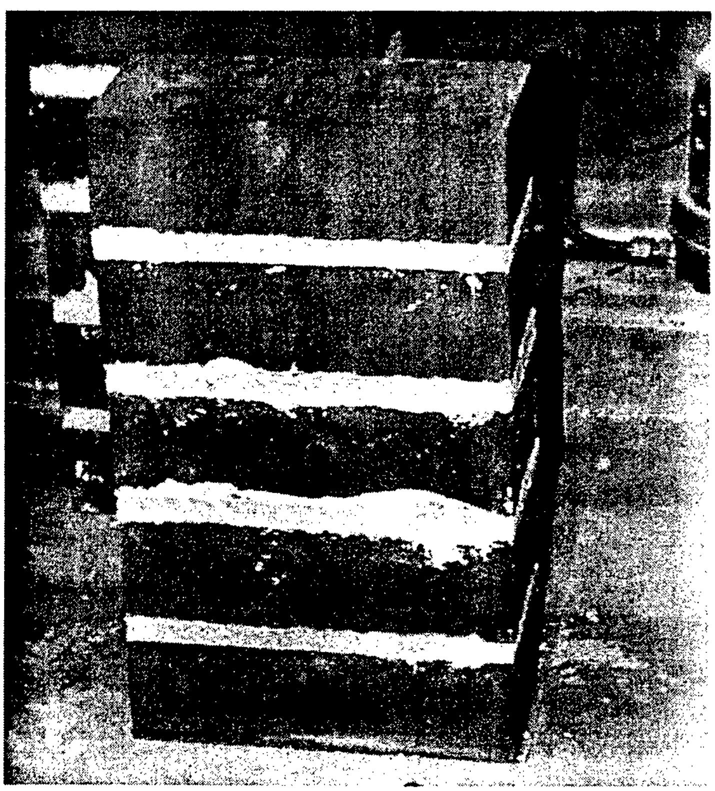

Figure 5. Brick prism.

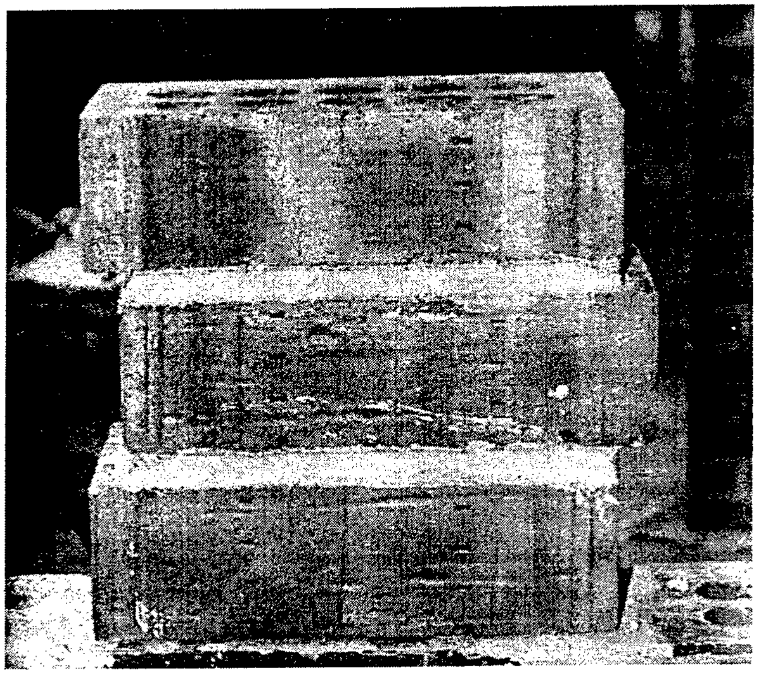

Figure 6. Brick triplet.

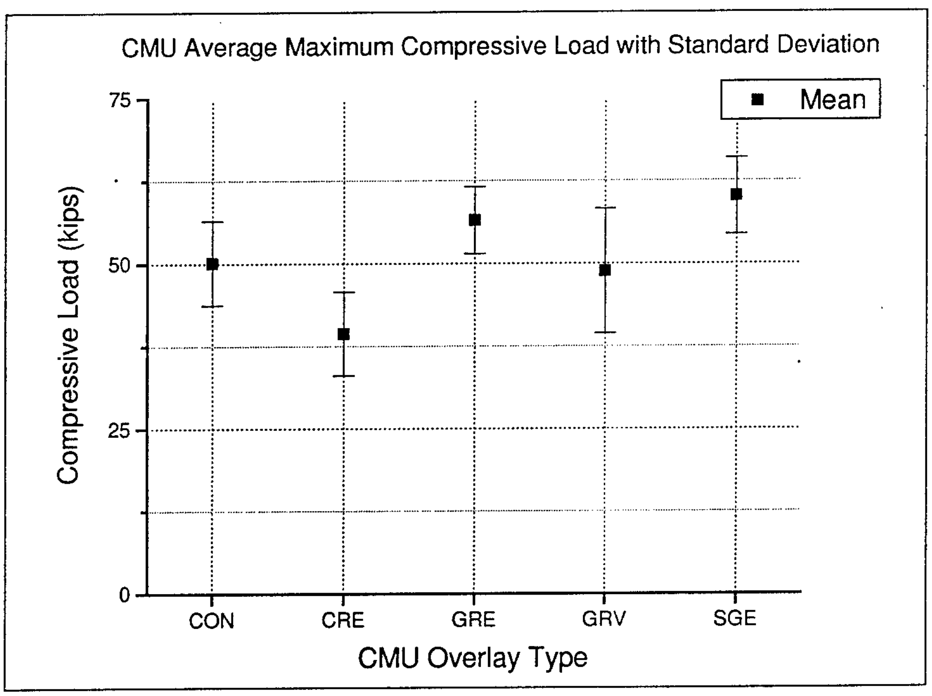

Figure 7. Average diagonal tension test failure loads vs the overlay type of CMU.

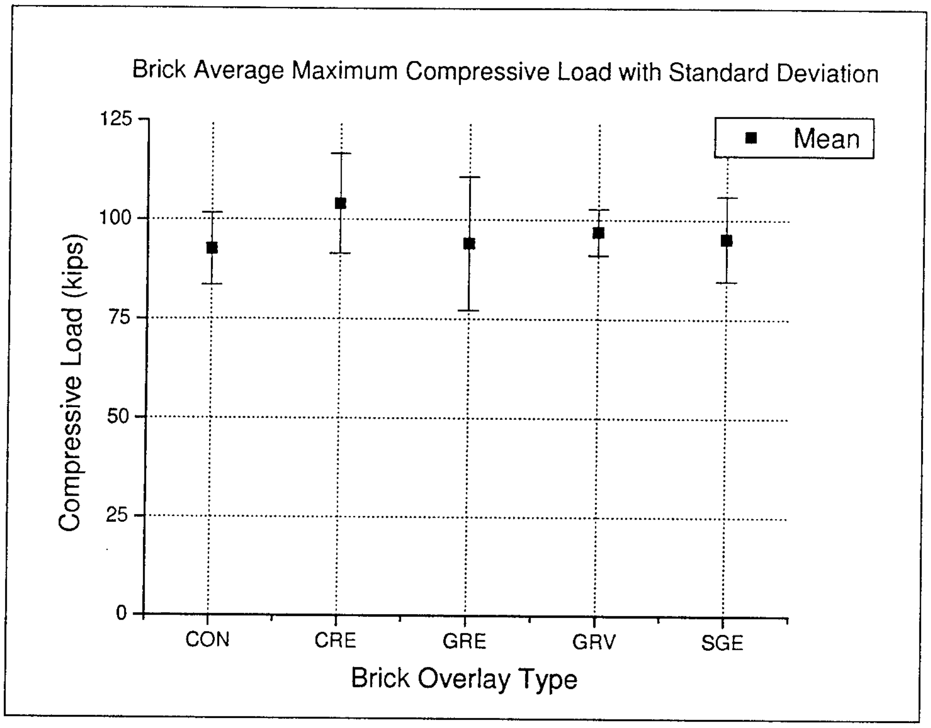

Figure 8. Average diagonal tension test failure loads vs the overlay type for brick.

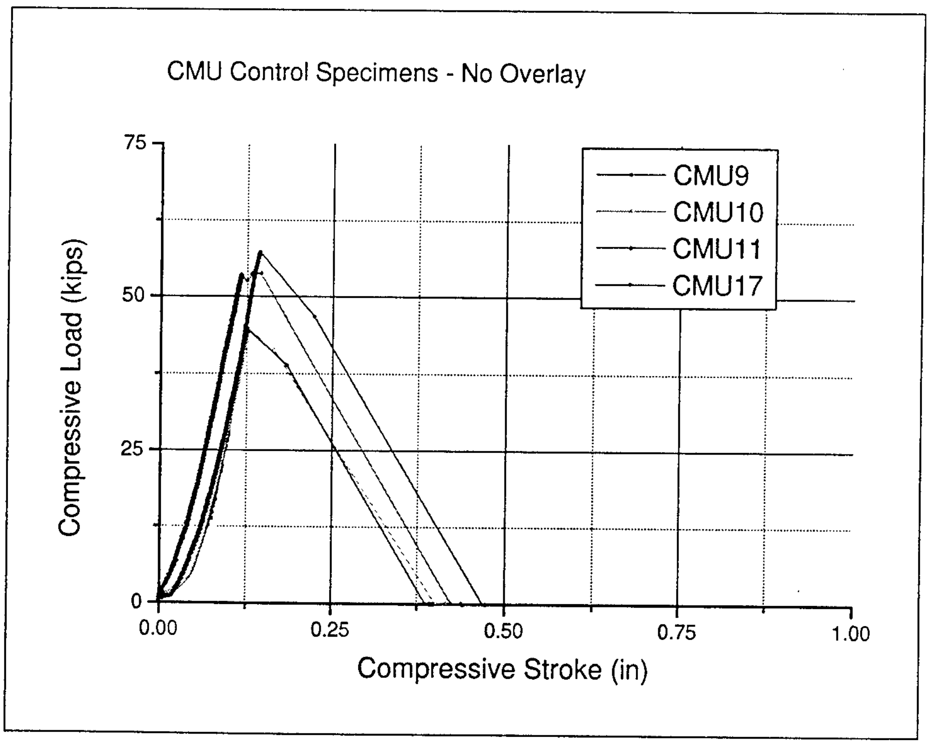

Figure 9. Diagonal tension test load/deflection curves for the CMU control specimens.

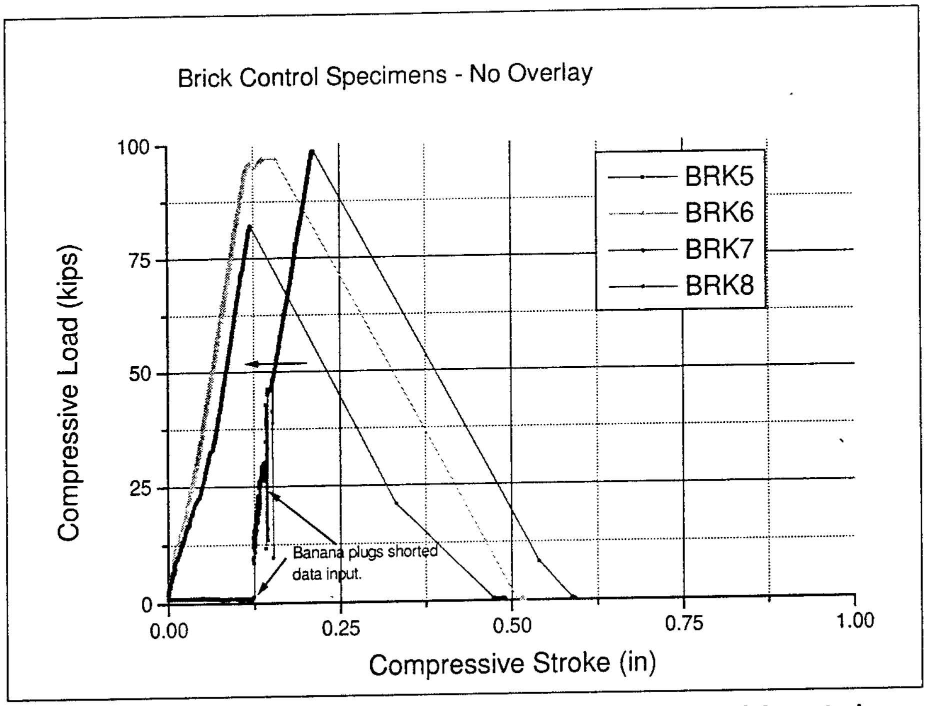

Figure 10. Diagonal tension test load/deflection curves for the brick control specimens.

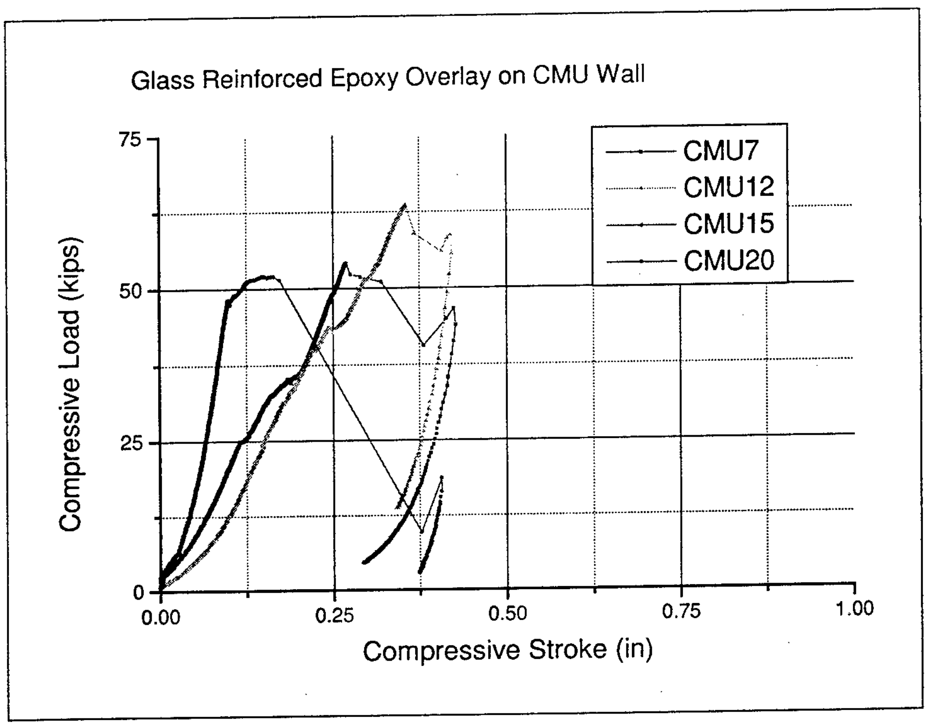

Figure 11. Diagonal tension test load/deflection curves for the glass-epoxy FRP system on CMU walls.

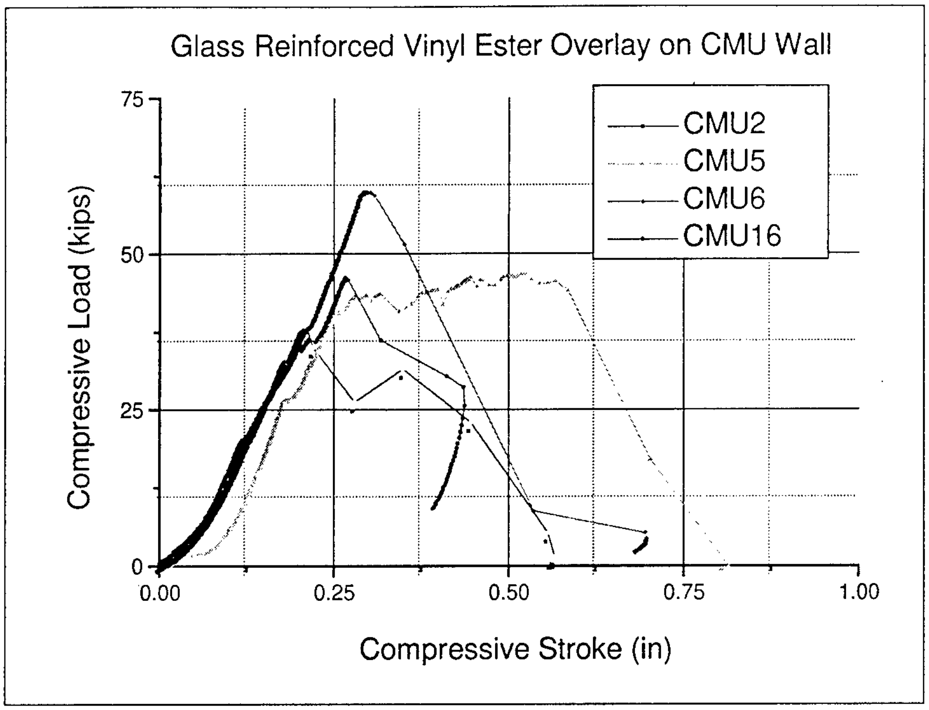

Figure 12. Diagonal tension test load/deflection curves for the glass-vinyl ester FRP system on CMU walls.

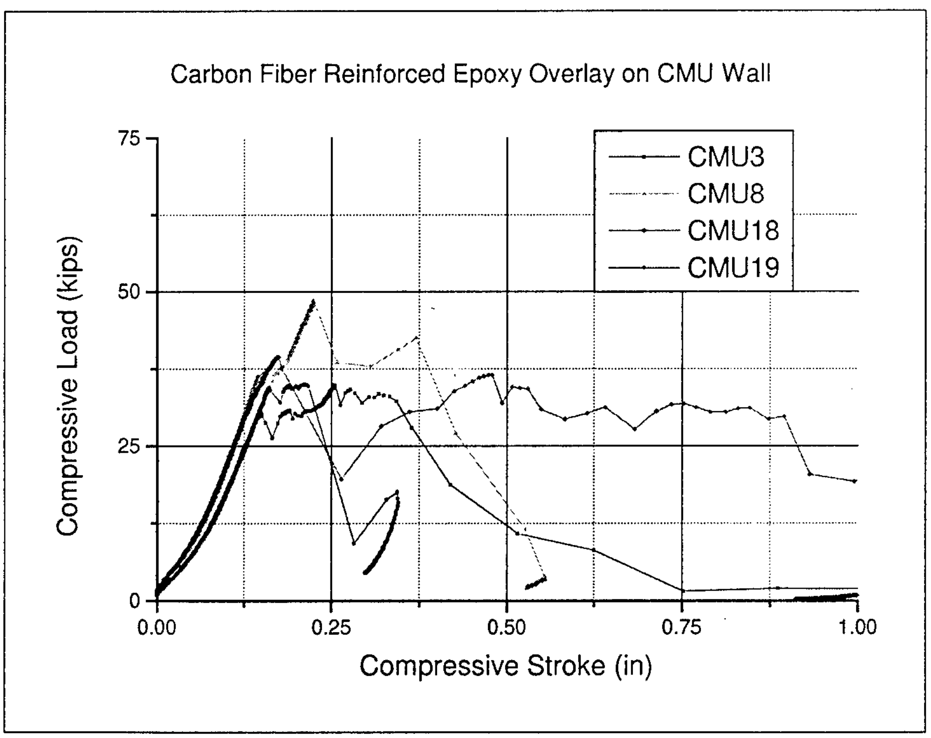

Figure 13. Diagonal tension test load/deflection curves for the carbon-epoxy FRP system on CMU walls.

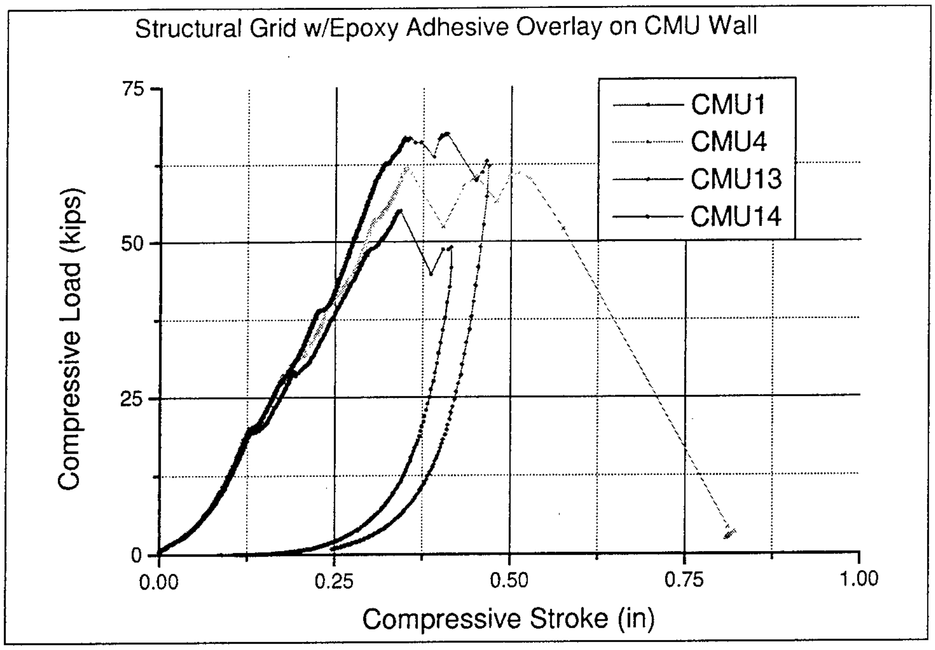

Figure 14. Diagonal tension test load/deflection curves for the glass-epoxy grid FRP system on CMU walls.

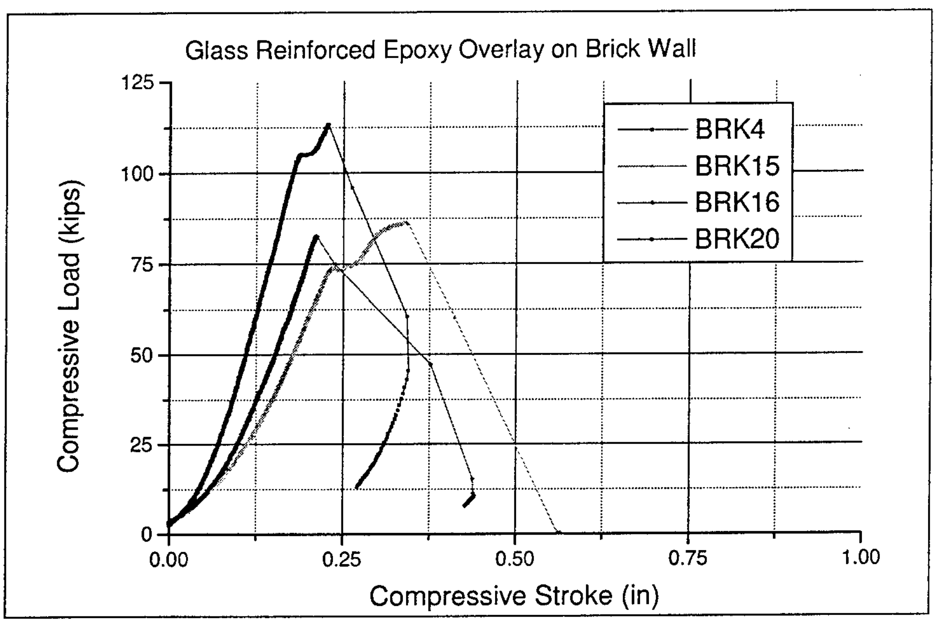

Figure 15. Diagonal tension test load/deflection curves for the glass-epoxy FRP system on brick walls.

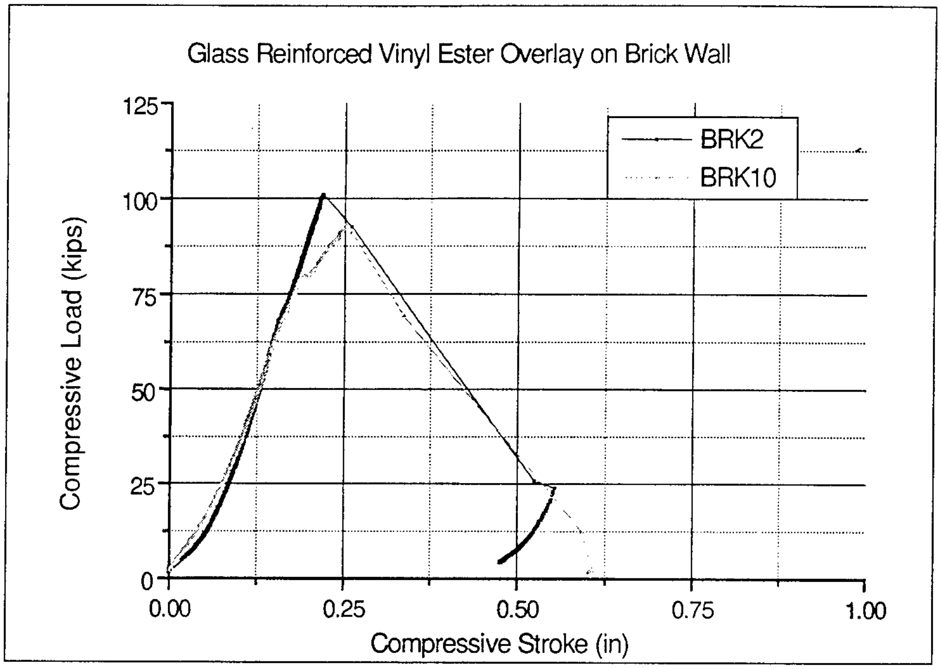

Figure 16. Diagonal tension test load/deflection curves for the glass-vinyl ester FRP system on brick walls.

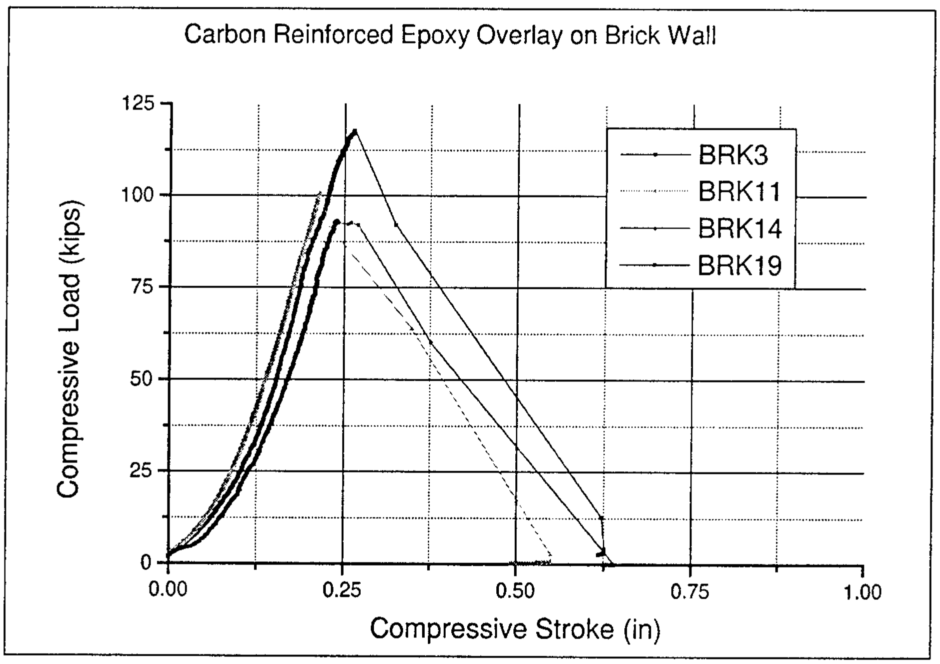

Figure 17. Diagonal tension test load/deflection curves for the carbon epoxy FRP system on brick walls.

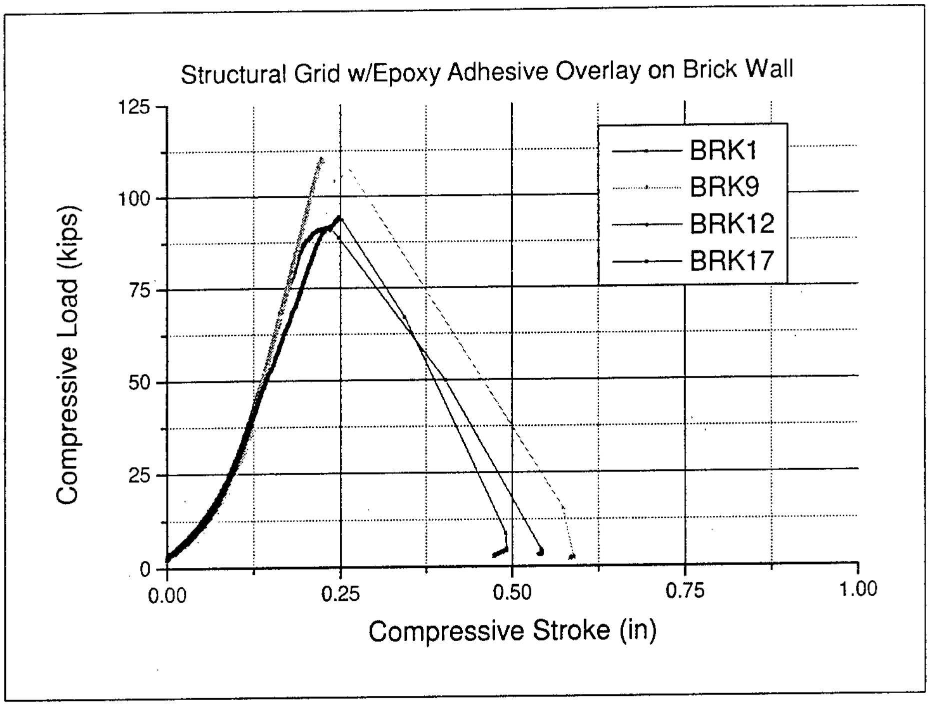

Figure 18. Diagonal tension test load/deflection curves for the glass epoxy grid FRP system on brick walls.

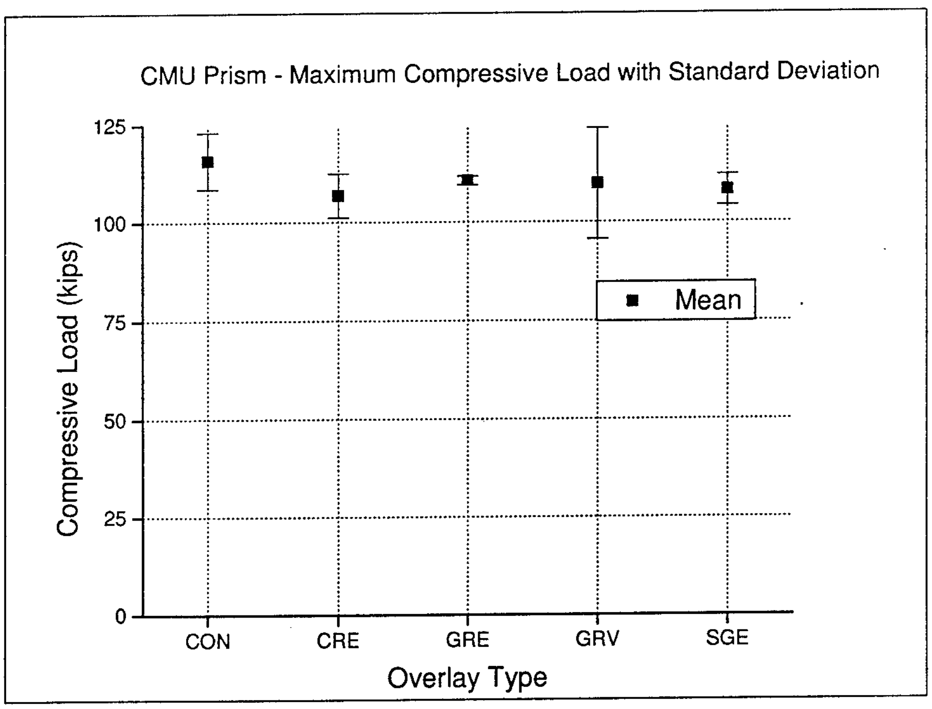

Figure 19. Average failure loads vs FRP configuration for CMU prisms.

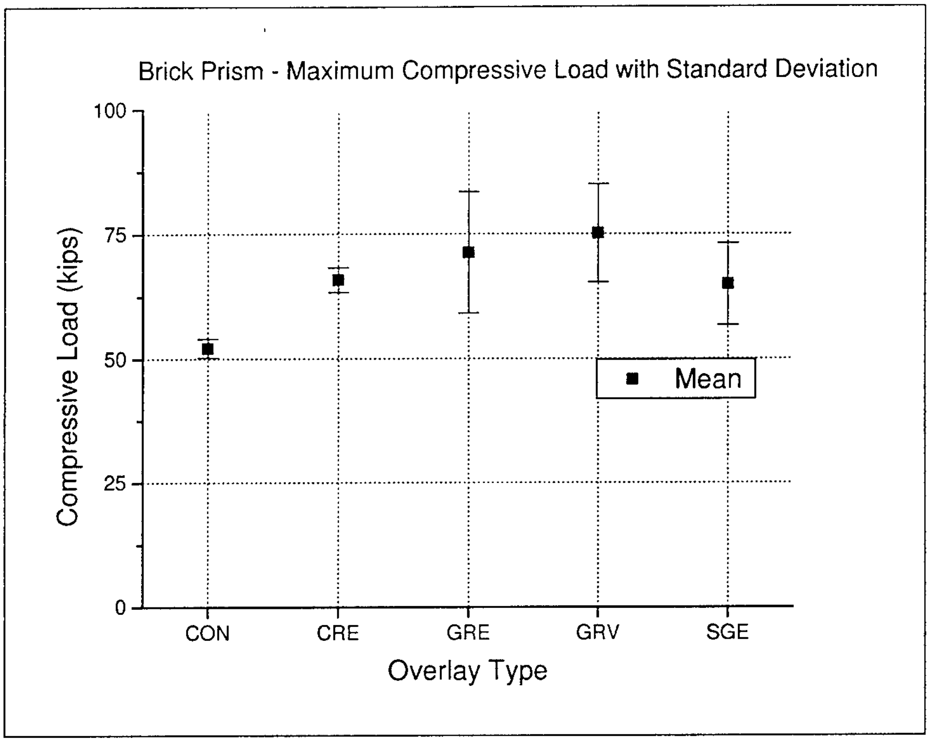

Figure 20. Average failure loads vs FRP configuration for brick prisms.

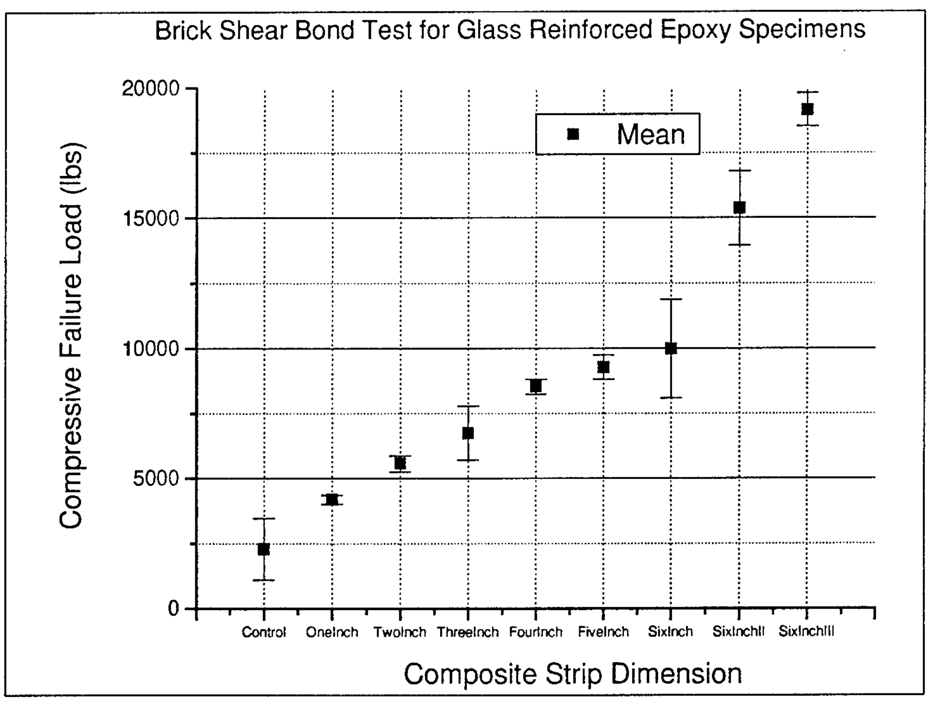

Figure 21. Average failure loads vs FRP configuration for glass epoxy triplets.

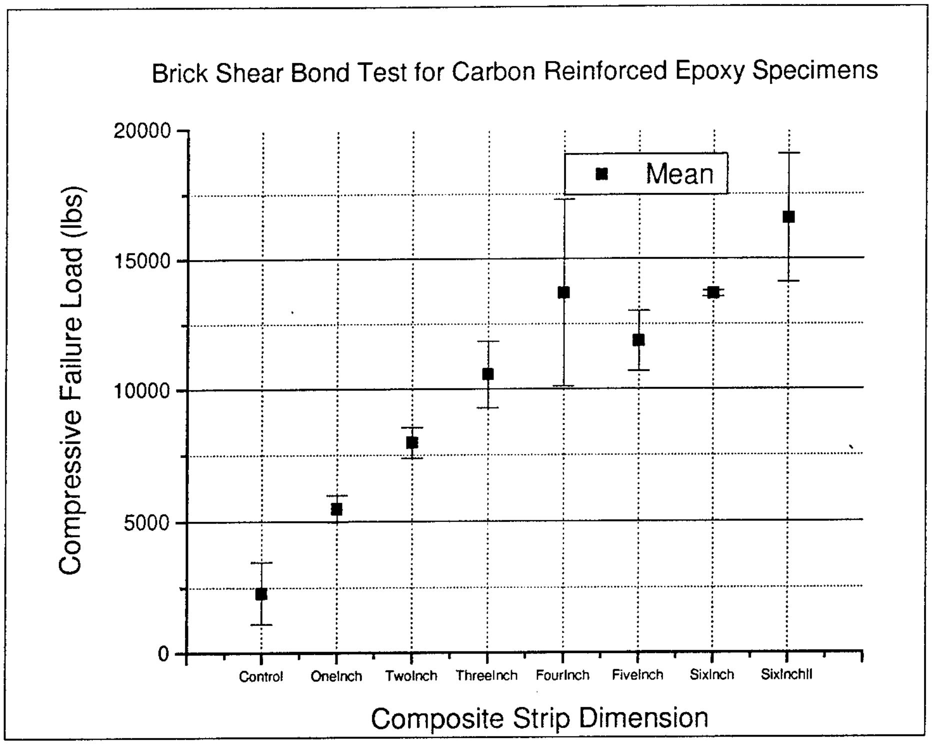

Figure 22. Average failure loads vs FRP configuration for carbon epoxy triplets.

Appendix A: Masonry Wall Test Data

Table A-1. CMU wall diagonal tension test data.

Wall Number	FRP Type	Mortar Strength (psi)	FRP Density (pcf)	FRP Coverage (psf)	Wall Strength (kips)
1	Structural Grid /w Epoxy Adhesive	1577	67.1	0.82	56.1
2	Glass Reinforced Vinyl Ester	1577	76.3	0.3	38.5
3	Carbon Reinforced Epoxy	1577	53.5	0.1	34.9
4	Structural Grid /w Epoxy Adhesive	1577	67.1	0.82	62.1
5	Glass Reinforced Vinyl Ester	1319	76.3	0.3	48
6	Glass Reinforced Vinyl Ester	1319	76.3	0.3	61.3
7	Glass Reinforced Epoxy	1319	83.3	0.28	54.1
8	Carbon Reinforced Epoxy	1319	53.5	0.1	48.4
9	N/A	1319	0	0	57.2
10	N/A	1319	0	0	44.8
11	N/A	1319	0	0	53.8
12	Glass Reinforced Epoxy	1659	83.3	0.28	63.6
13	Structural Grid /w Epoxy Adhesive	1659	67.1	0.82	67.4
14	Structural Grid /w Epoxy Adhesive	1659	67.1	0.82	55
15	Glass Reinforced Epoxy	1806	83.3	0.28	56.3
16	Glass Reinforced Vinyl Ester	1806	76.3	0.3	47.6
17	N/A	1806	0	0	44.7
18	Carbon Reinforced Epoxy	1612	53.5	0.1	39.4
19	Carbon Reinforced Epoxy	1612	53.5	0.1	35
20	Glass Reinforced Epoxy	1803	83.3	0.28	52

Table A-2. Brick wall diagonal tension test data.

Wall Number	FRP Type	Mortar Strength (psi)	FRP Density (pcf)	FRP Coverage (psf)	Wall Strength (kips)
1	Structural Grid /w Epoxy Adhesive	1612	67.1	0.82	94.2
2	Glass Reinforced Vinyl Ester	1803	76.3	0.3	101
3	Carbon Reinforced Epoxy	1945	53.5	0.1	117.9
4	Glass Reinforced Epoxy	2195	83.3	0.28	113.3
5	N/A	2220	0	0	98.5
6	N/A	2220	0	0	96.9
7	N/A	2363	0	0	91.8
8	N/A	2090	0	0	82.1
9	Structural Grid /w Epoxy Adhesive	2533	67.1	0.82	110.2
10	Glass Reinforced Vinyl Ester	1488	76.3	0.3	92.8
11	Carbon Reinforced Epoxy	1790	53.5	0.1	100.7
12	Structural Grid /w Epoxy Adhesive	2159 2337	67.1	0.82	85.2
13	Glass Reinforced Vinyl Ester	2337 2259	76.3	0.3	Damaged
14	Carbon Reinforced Epoxy	2259 2446	53.5	0.1	Damaged
15	Glass Reinforced Epoxy	2233	83.3	0.28	86.1
16	Glass Reinforced Epoxy	1636	83.3	0.28	82.6
17	Structural Grid /w Epoxy Adhesive	1745 2732	67.1	0.82	91.2
18	Glass Reinforced Vinyl Ester	2732 2233	76.3	0.3	32.2*
19	Carbon Reinforced Epoxy	2539 2075	53.5	0.1	93.3
20	Glass Reinforced Epoxy	2075 1737	83.3	0.28	81

* Racking test load

Appendix B: Wall Crack Patterns

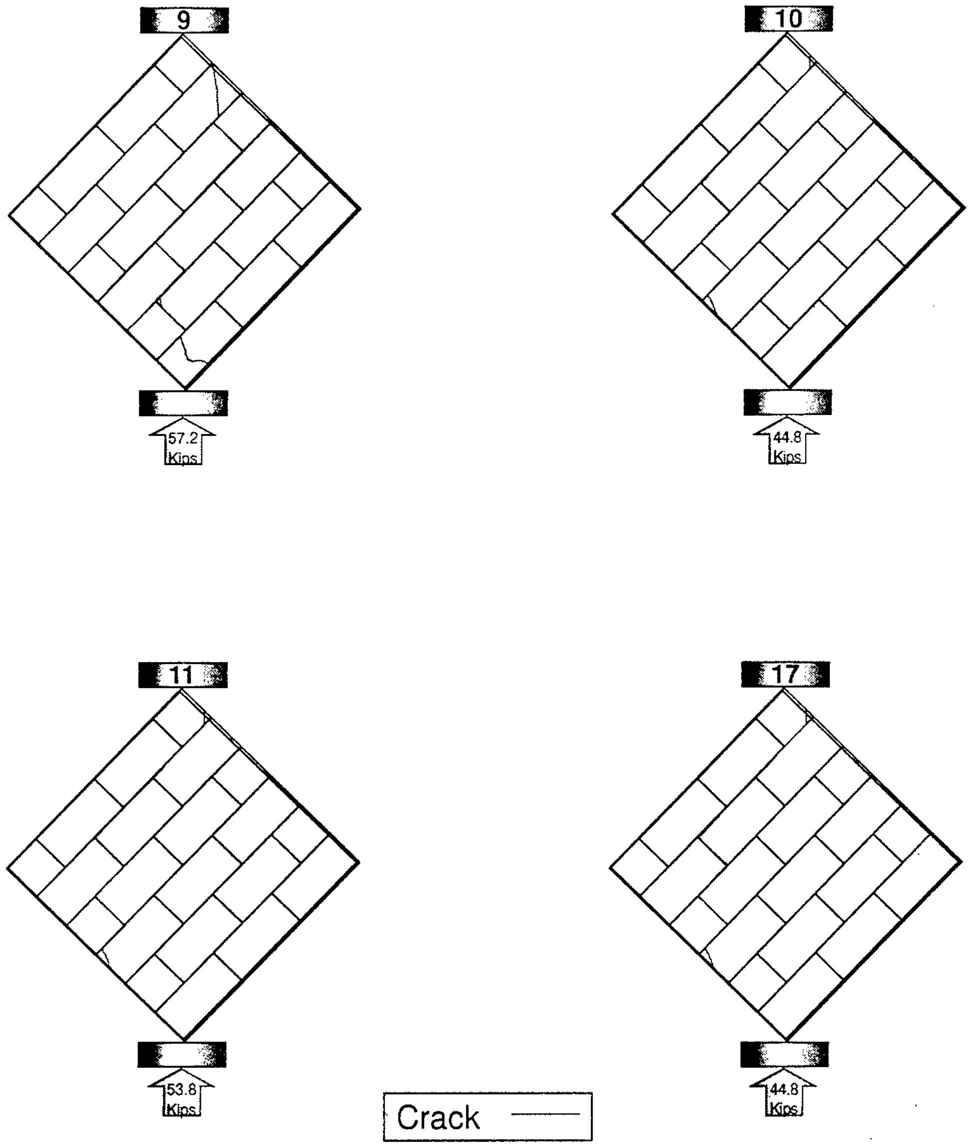

Figure 23. CMU controls.

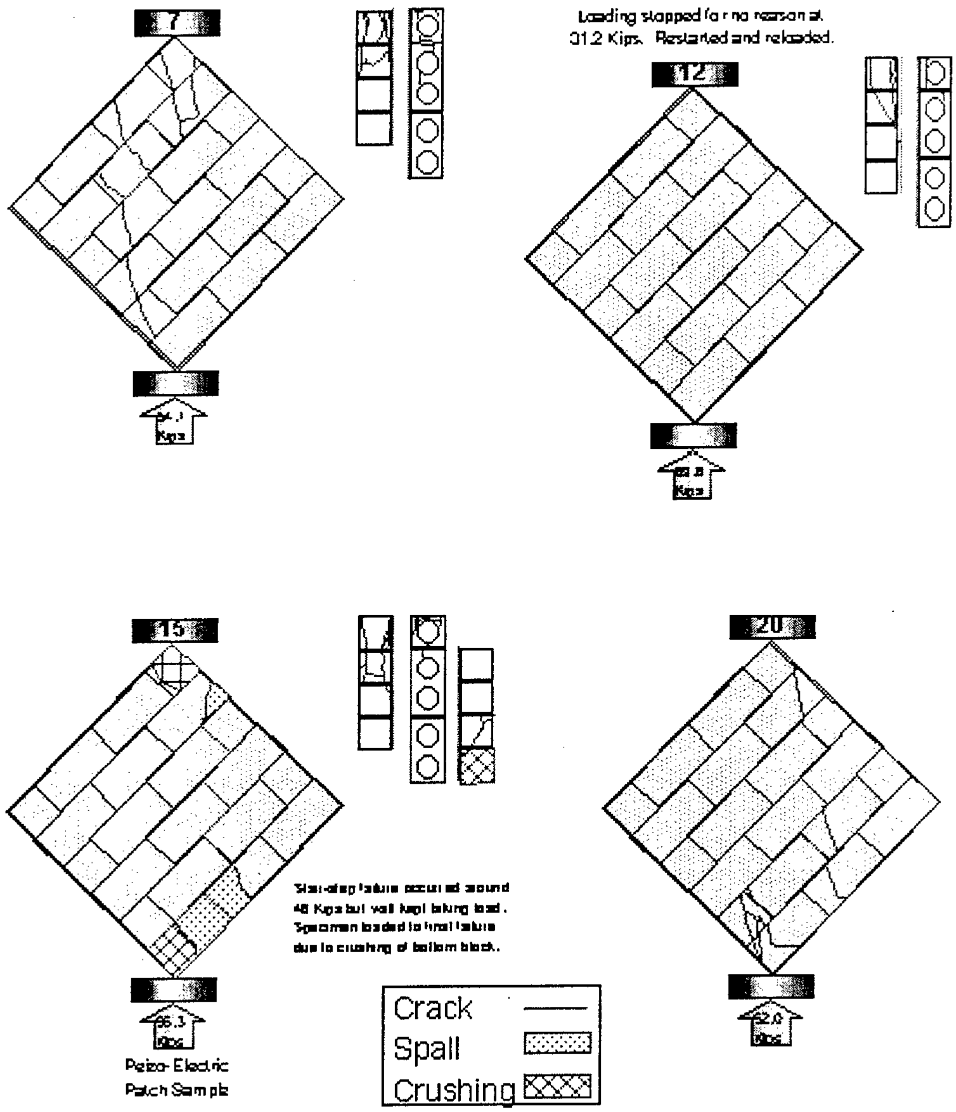

Figure 24. CMU w/glass-epoxy FRP overlay.

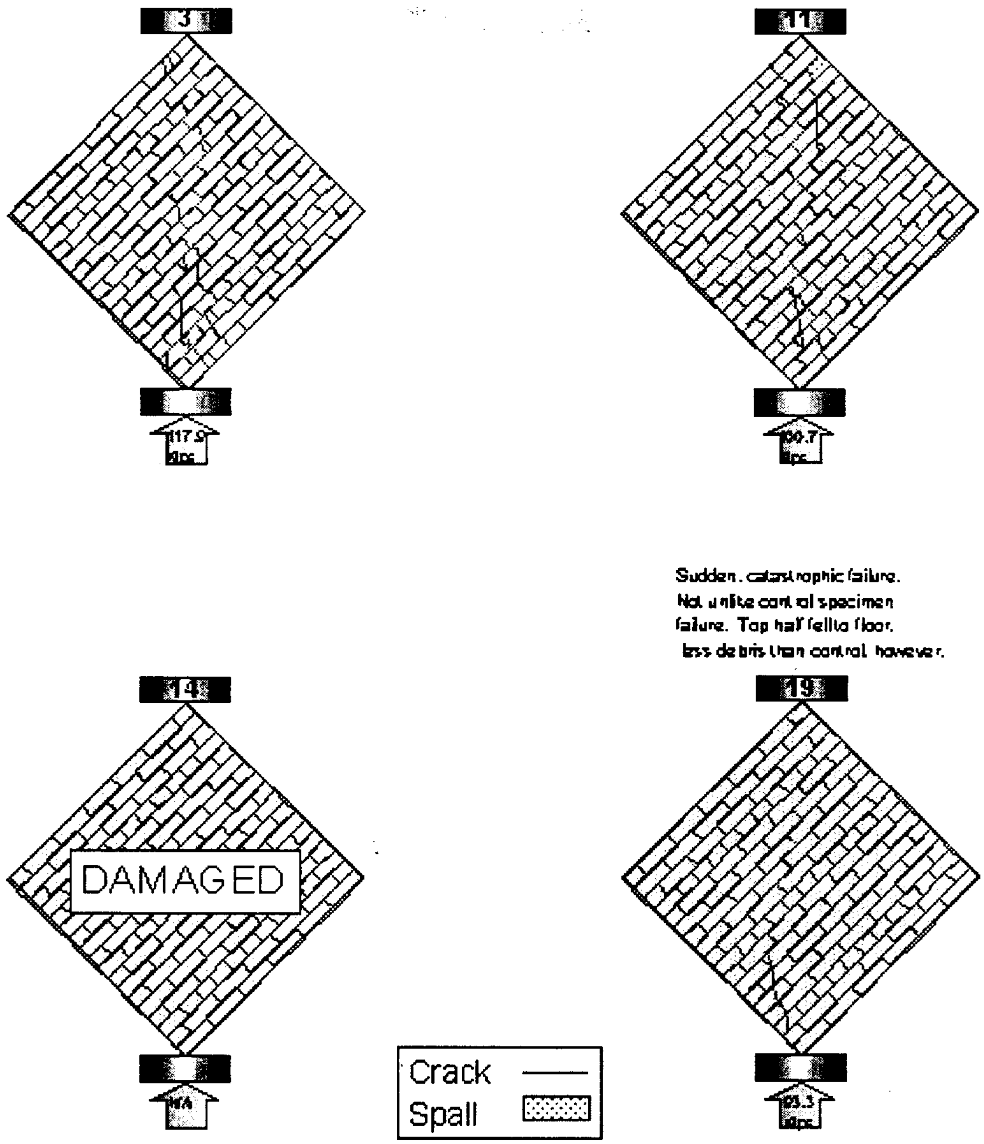

Figure 25. Brick w/carbon-epoxy FRP overlay.

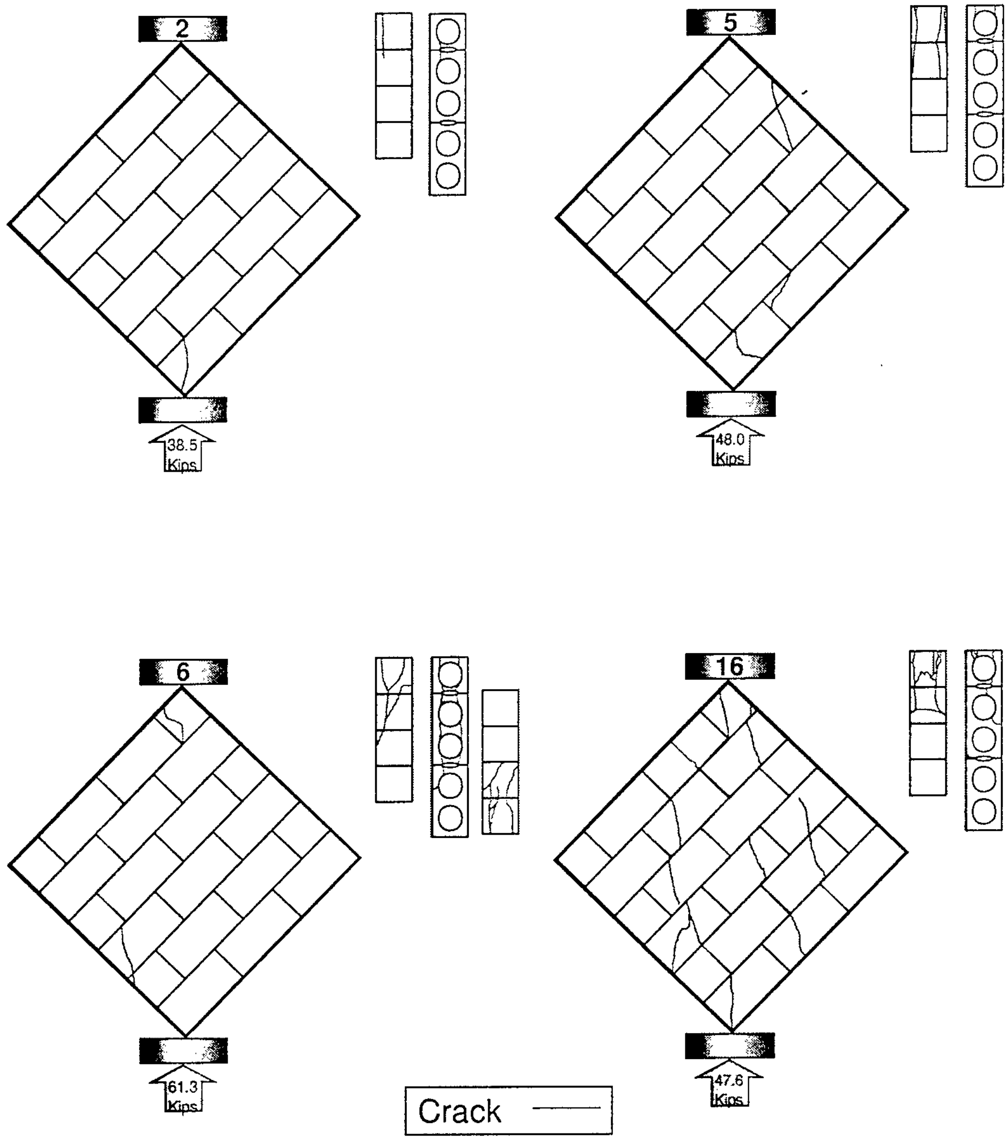

Figure 26. CMU w/glass-vinyl ester FRP overlay.

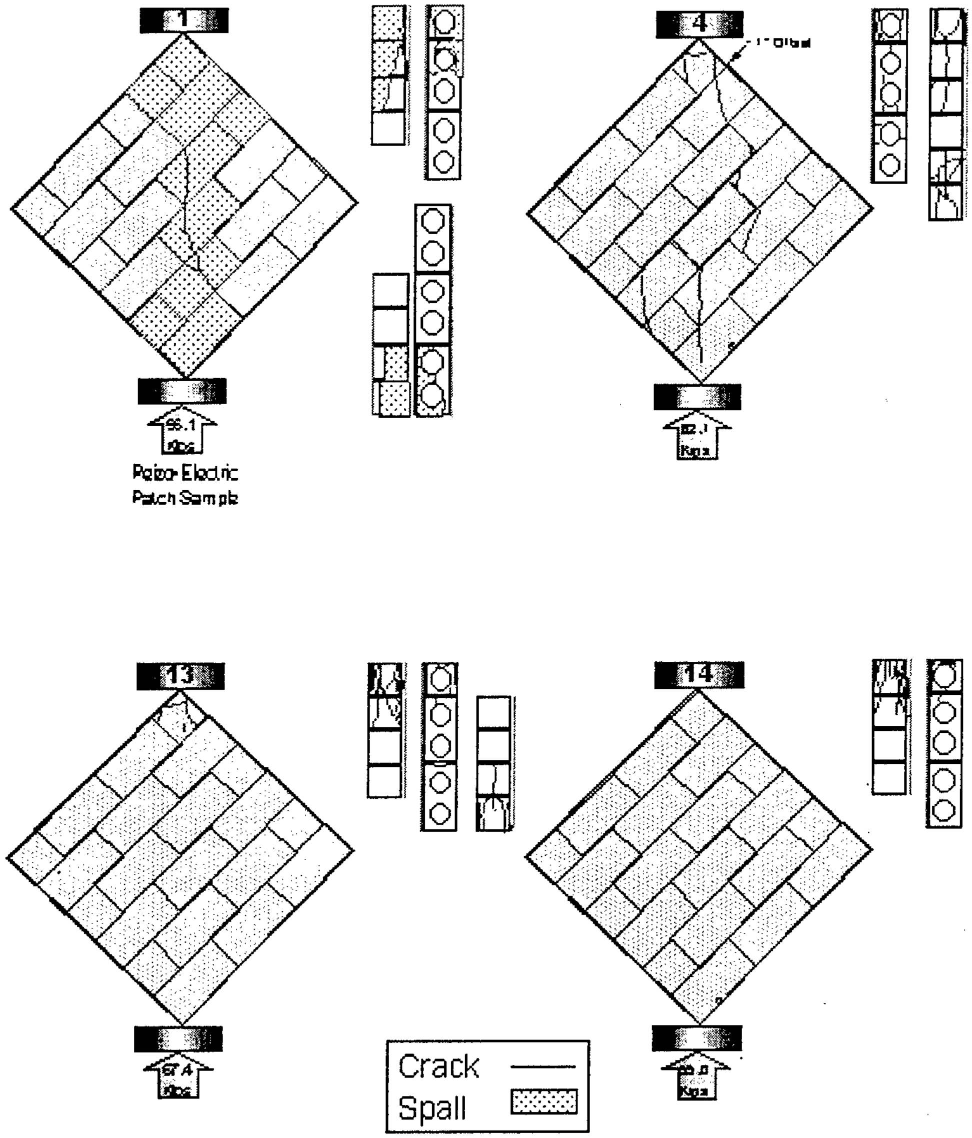

Figure 27. CMU w/structural grid FRP overlay.

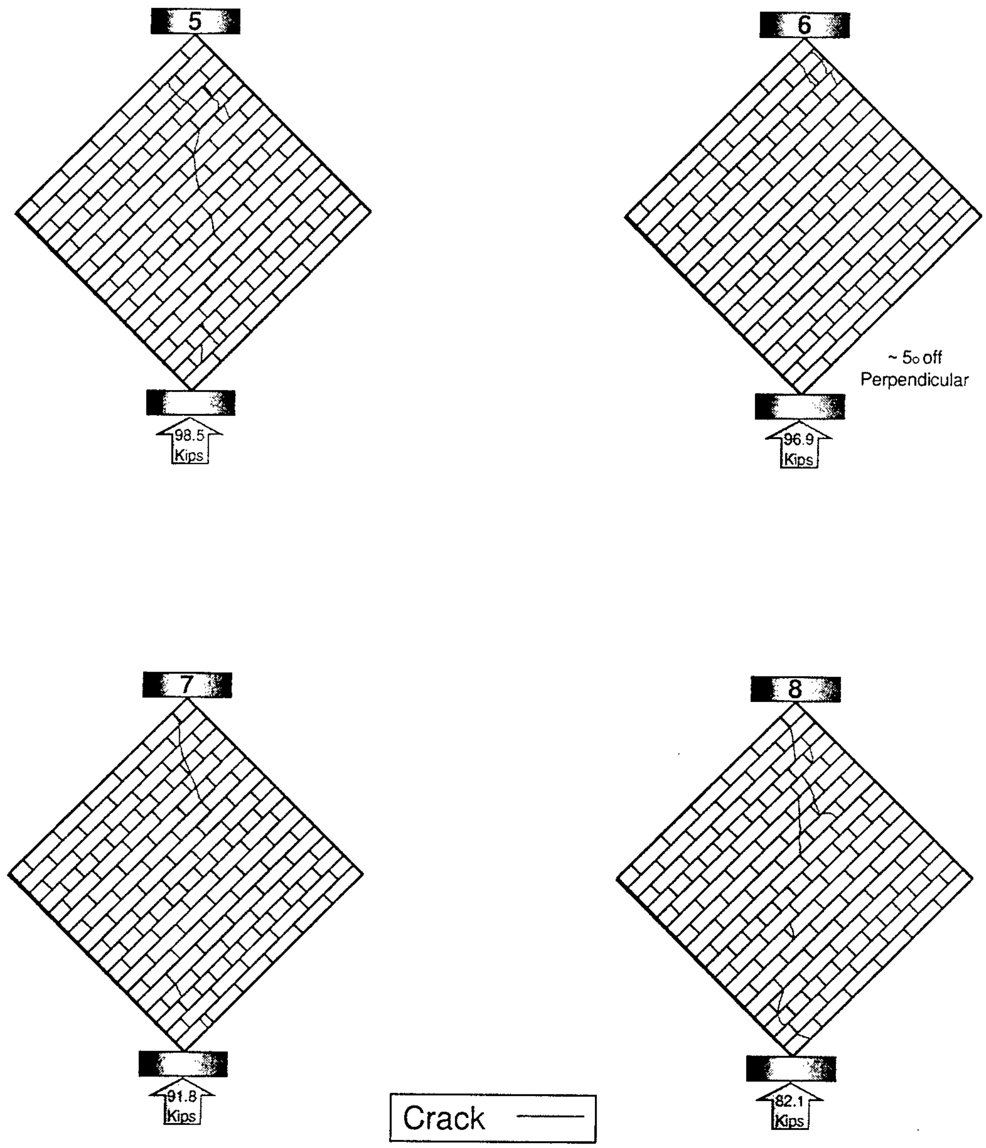

Figure 28. Brick controls.

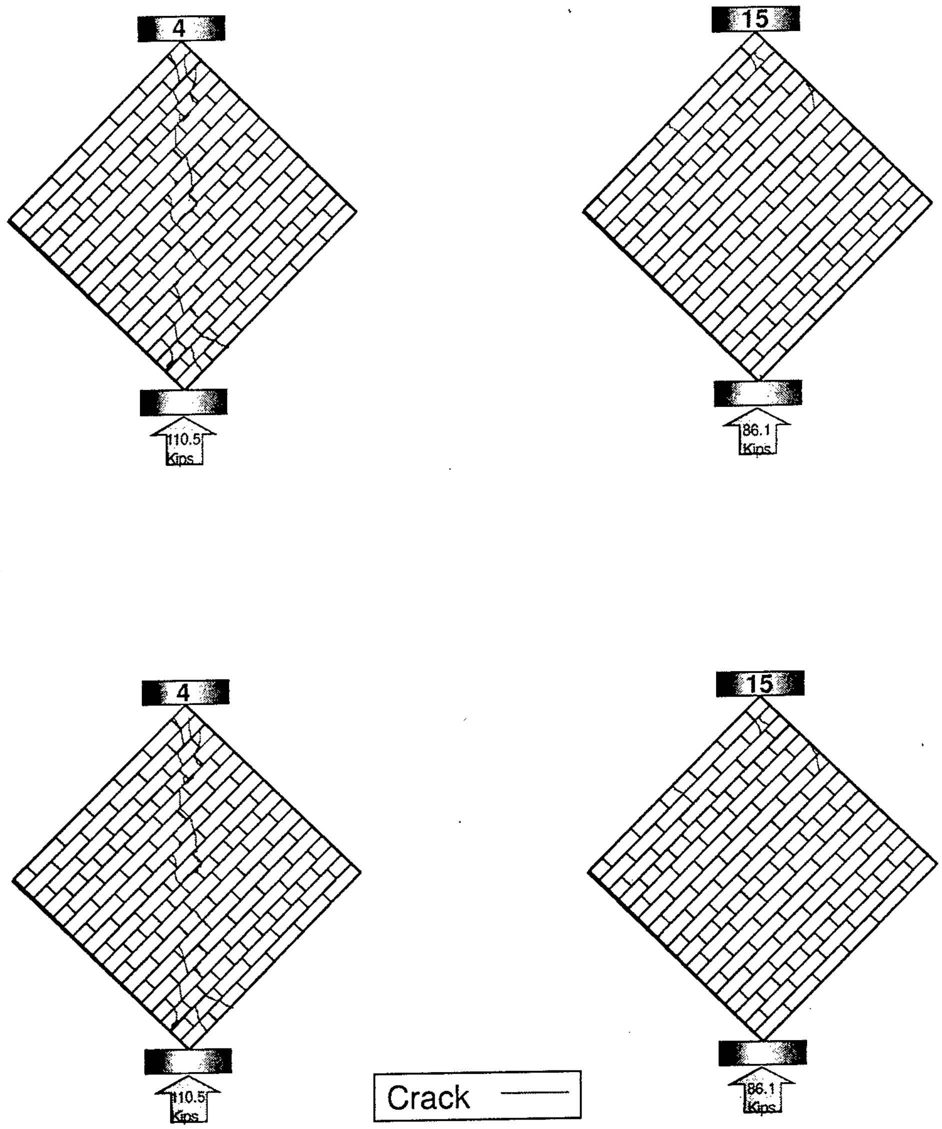

Figure 29. Brick w/glass-epoxy FRP overlay.

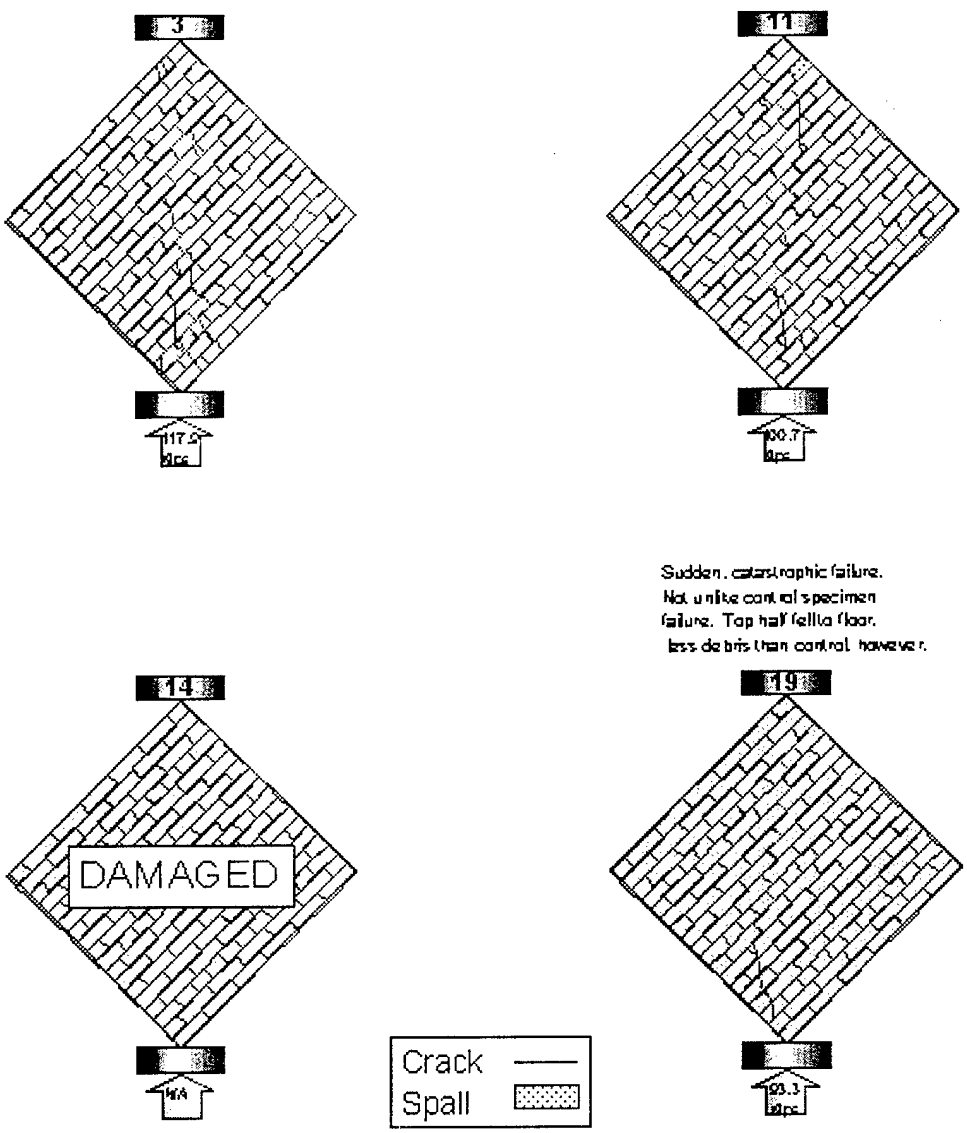

Figure 30. Brick w/carbon-epoxy FRP overlay.

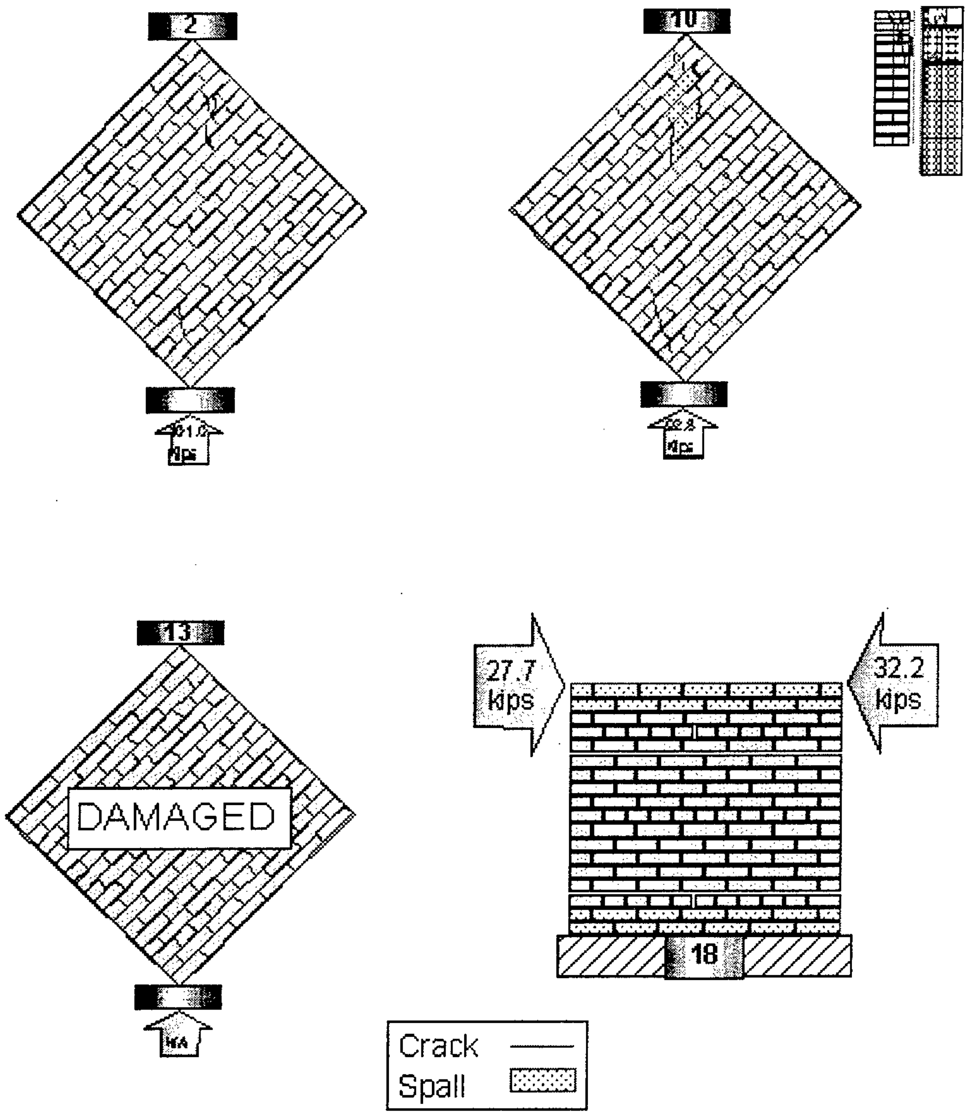

Figure 31. Brick w/glass-vinyl ester FRP overlay.

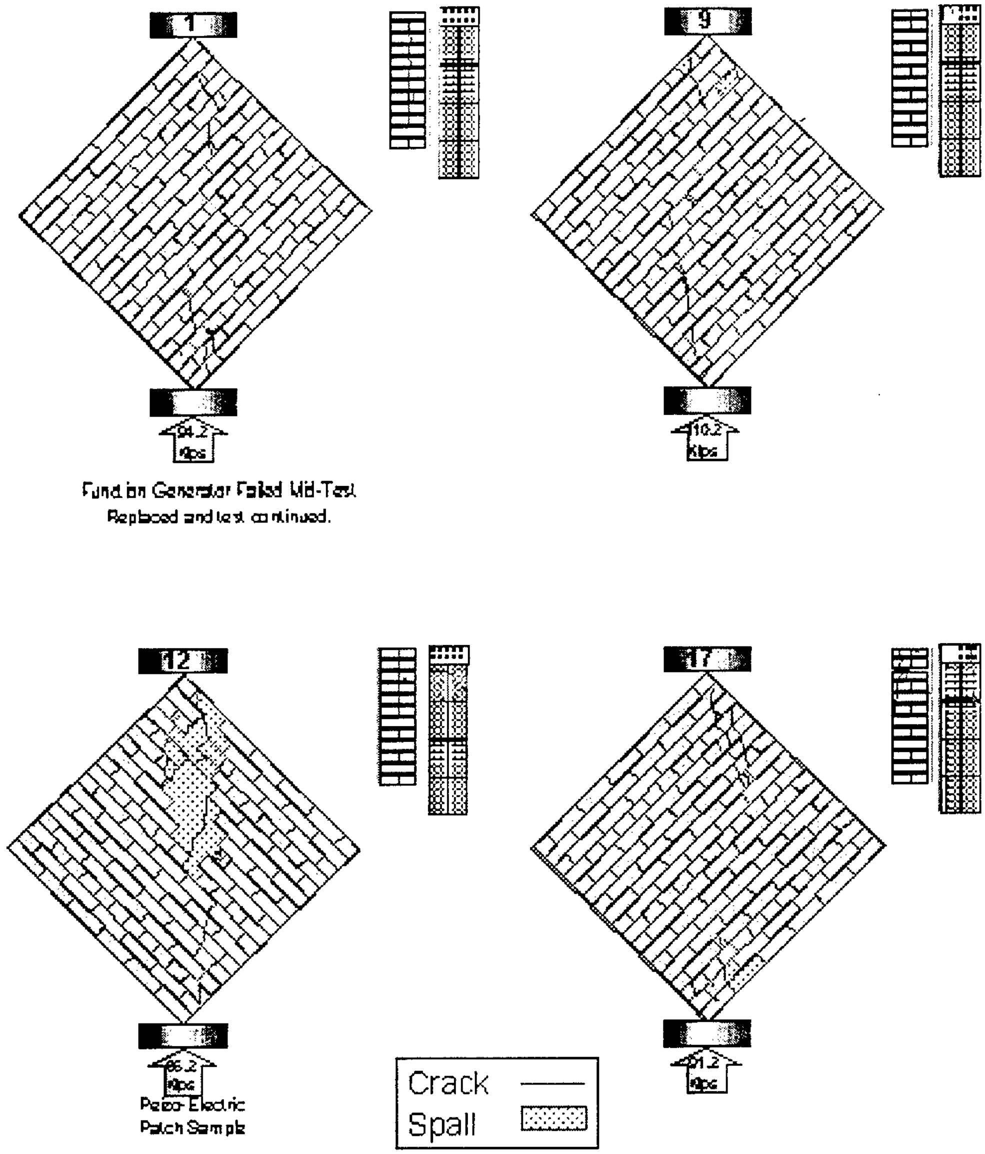

Figure 32. Brick w/structural grid FRP overlay.

Appendix C: Mortar Cube Properties

Table C-1. Mortar cube test data.

SAMPLE NUMBER	MIX DATE	TEST DATE	A (sq in.)	P (lb)	f_c (psi)	STD DEV
BATCH 1	12/22/97	*n/a*	*n/a*	*n/a*	**1577.08**	199.97
specimen A	12/22/97	1/22/98	4	6624.7	1656.18	
specimen B	12/22/97	1/22/98	4	5398.6	1349.65	
specimen C	12/22/97	1/22/98	4	6901.6	1725.40	
BATCH 2	12/22/97	*n/a*	*n/a*	*n/a*	**1319.22**	102.00
specimen A	12/22/97	1/22/98	4	5330.0	1332.50	
specimen B	12/22/97	1/22/98	4	5655.7	1413.93	
specimen C	12/22/97	1/22/98	4	4844.9	1211.23	
BATCH 3	12/22/97	*n/a*	*n/a*	*n/a*	**1659.48**	220.56
specimen A	12/22/97	1/22/98	4	6328.1	1582.03	
specimen B	12/22/97	1/22/98	4	7633.3	1908.33	
specimen C	12/22/97	1/22/98	4	5952.4	1488.10	
BATCH 4	12/23/97	*n/a*	*n/a*	*n/a*	**1806.29**	84.86
specimen A	12/23/97	1/22/98	4	7534.4	1883.60	
specimen B	12/23/97	1/22/98	4	6862.0	1715.50	
specimen C	12/23/97	1/22/98	4	7279.1	1819.78	
BATCH 5	12/23/97	*n/a*	*n/a*	*n/a*	**1611.68**	69.22
specimen A	12/23/97	1/22/98	4	6130.3	1532.58	
specimen B	12/23/97	1/22/98	4	6644.5	1661.13	
specimen C	12/23/97	1/22/98	4	6565.4	1641.35	
BATCH 6	12/23/97	*n/a*	*n/a*	*n/a*	**1802.85**	76.81
specimen A	12/23/97	1/22/98	4	7119.1	1779.78	
specimen B	12/23/97	1/22/98	4	6960.9	1740.23	
specimen C	12/23/97	1/22/98	4	7554.2	1888.55	
BATCH 7	12/23/97	*n/a*	*n/a*	*n/a*	**1860.53**	32.92
specimen A	12/23/97	1/22/98	4	7376.2	1844.05	
specimen B	12/23/97	1/22/98	4	7593.7	1898.43	
specimen C	12/23/97	1/22/98	4	7356.4	1839.10	
BATCH 8	12/26/97	*n/a*	*n/a*	*n/a*	**1944.57**	196.80
specimen A	12/26/97	1/22/98	4	7237.7	1809.43	
specimen B	12/26/97	1/22/98	4	8681.4	2170.35	
specimen C	12/26/97	1/22/98	4	7415.7	1853.93	
BATCH 9	12/26/97	*n/a*	*n/a*	*n/a*	**2195.06**	113.28
specimen A	12/26/97	1/22/98	4	8681.4	2170.35	
specimen B	12/26/97	1/22/98	4	9274.6	2318.65	
specimen C	12/26/97	1/22/98	4	8384.7	2096.18	

SAMPLE NUMBER	MIX DATE	TEST DATE	A (sq in.)	P (lb)	f_c (psi)	STD DEV
BATCH 10	12/26/97	*n/a*	*n/a*	*n/a*	**2219.78**	114.99
specimen A	12/26/97	1/22/98	4	8958.2	2239.55	
specimen B	12/26/97	1/22/98	4	9294.4	2323.60	
specimen C	12/26/97	1/22/98	4	8384.7	2096.18	
BATCH 11	12/26/97	*n/a*	*n/a*	*n/a*	**2025.30**	44.87
specimen A	12/26/97	1/22/98	4	7969.4	1992.35	
specimen B	12/26/97	1/22/98	4	8305.6	2076.40	
specimen C	12/26/97	1/22/98	4	8028.6	2007.15	
BATCH 12	12/29/97	*n/a*	*n/a*	*n/a*	**1990.72**	123.13
specimen A	12/29/97	1/30/98	4	8206.7	2051.68	
specimen B	12/29/97	1/30/98	4	8285.9	2071.48	
specimen C	12/29/97	1/30/98	4	7396.0	1849.00	
BATCH 13	12/29/97	*n/a*	*n/a*	*n/a*	**2363.10**	264.19
specimen A	12/29/97	1/30/98	4	8325.4	2081.35	
specimen B	12/29/97	1/30/98	4	10421.0	2605.25	
specimen C	12/29/97	1/30/98	4	9610.8	2402.70	
BATCH 14	12/29/97	*n/a*	*n/a*	*n/a*	**2089.59**	198.76
specimen A	12/29/97	1/30/98	4	7949.7	1987.43	
specimen B	12/29/97	1/30/98	4	9274.6	2318.65	
specimen C	12/29/97	1/30/98	4	7850.8	1962.70	
BATCH 15	12/29/97	*n/a*	*n/a*	*n/a*	**2125.84**	206.64
specimen A	12/29/97	1/30/98	4	7850.8	1962.70	
specimen B	12/29/97	1/30/98	4	9432.8	2358.20	
specimen C	12/29/97	1/30/98	4	8226.5	2056.63	
BATCH 16	12/30/97	*n/a*	*n/a*	*n/a*	**2532.83**	134.10
specimen A	12/30/97	1/30/98	4	10441.0	2610.25	
specimen B	12/30/97	1/30/98	4	10441.0	2610.25	
specimen C	12/30/97	1/30/98	4	9511.9	2377.98	
BATCH 17	12/30/97	*n/a*	*n/a*	*n/a*	**1488.08**	137.62
specimen A	12/30/97	1/30/98	4	6051.2	1512.80	
specimen B	12/30/97	1/30/98	4	5359.1	1339.78	
specimen C	12/30/97	1/30/98	4	6446.7	1611.68	
BATCH 18	12/30/97	*n/a*	*n/a*	*n/a*	**1789.66**	72.83
specimen A	12/30/97	1/30/98	4	6842.2	1710.55	
specimen B	12/30/97	1/30/98	4	7415.7	1853.93	
specimen C	12/30/97	1/30/98	4	7218.0	1804.50	

SAMPLE NUMBER	MIX DATE	TEST DATE	A (sq in.)	P (lb)	f_c (psi)	STD DEV
BATCH 19	12/30/97	*n/a*	*n/a*	*n/a*	**2158.80**	105.61
specimen A	12/30/97	1/30/98	4	8147.4	2036.85	
specimen B	12/30/97	1/30/98	4	8879.1	2219.78	
specimen C	12/30/97	1/30/98	4	8879.1	2219.78	
BATCH 20	12/31/97	*n/a*	*n/a*	*n/a*	**2337.35**	48.87
specimen A	12/31/97	1/30/98	4	9143.0	2285.75	
specimen B	12/31/97	1/30/98	4	9373.5	2343.38	
specimen C	12/31/97	1/30/98	4	9531.7	2382.93	
BATCH 21	12/31/97	*n/a*	*n/a*	*n/a*	**2259.33**	94.72
specimen A	12/31/97	1/30/98	4	8602.2	2150.55	
specimen B	12/31/97	1/30/98	4	9215.3	2303.83	
specimen C	12/31/97	1/30/98	4	9294.4	2323.60	
BATCH 22	12/31/97	*n/a*	*n/a*	*n/a*	**2445.55**	56.23
specimen A	12/31/97	1/30/98	4	9531.7	2382.93	
specimen B	12/31/97	1/30/98	4	9848.1	2462.03	
specimen C	12/31/97	1/30/98	4	9966.8	2491.70	
BATCH 23	12/31/97	*n/a*	*n/a*	*n/a*	**2232.97**	91.74
specimen A	12/31/97	1/30/98	4	8582.5	2145.63	
specimen B	12/31/97	1/30/98	4	9314.2	2328.55	
specimen C	12/31/97	1/30/98	4	8898.9	2224.73	
BATCH 24	1/2/98	*n/a*	*n/a*	*n/a*	**1636.41**	82.58
specimen A	1/2/98	2/5/98	4	6486.3	1621.58	
specimen B	1/2/98	2/5/98	4	6901.6	1725.40	
specimen C	1/2/98	2/5/98	4	6249.0	1562.25	
BATCH 25	1/2/98	*n/a*	*n/a*	*n/a*	**1745.17**	47.16
specimen A	1/2/98	2/5/98	4	7178.4	1794.60	
specimen B	1/2/98	2/5/98	4	6960.9	1740.23	
specimen C	1/2/98	2/5/98	4	6802.7	1700.68	
BATCH 26	1/2/98	*n/a*	*n/a*	*n/a*	**2732.18**	238.32
specimen A	1/2/98	2/5/98	4	9927.2	2481.80	
specimen B	1/2/98	2/5/98	4	11825.0	2956.25	
specimen C	1/2/98	2/5/98	4	11034.0	2758.50	

SAMPLE NUMBER	MIX DATE	TEST DATE	A (sq in.)	P (lb)	f_c (psi)	STD DEV
BATCH 27	1/2/98	*n/a*	*n/a*	*n/a*	**2232.97**	20.58
specimen A	1/2/98	2/5/98	4	8839.6	2209.90	
specimen B	1/2/98	2/5/98	4	8997.8	2249.45	
specimen C	1/2/98	2/5/98	4	8958.2	2239.55	
BATCH 28	1/5/98	*n/a*	*n/a*	*n/a*	**2539.42**	28.15
specimen A	1/5/98	2/5/98	4	10065.0	2516.25	
specimen B	1/5/98	2/5/98	4	10125.0	2531.25	
specimen C	1/5/98	2/5/98	4	10283.0	2570.75	
BATCH 29	1/5/98	*n/a*	*n/a*	*n/a*	**2074.76**	247.50
specimen A	1/5/98	2/5/98	4	9116.4	2279.10	
specimen B	1/5/98	2/5/98	4	7198.2	1799.55	
specimen C	1/5/98	2/5/98	4	8582.5	2145.63	
BATCH 30	1/5/98	*n/a*	*n/a*	*n/a*	**1736.93**	154.31
specimen A	1/5/98	2/5/98	4	7099.3	1774.83	
specimen B	1/5/98	2/5/98	4	6268.8	1567.20	
specimen C	1/5/98	2/5/98	4	7475.0	1868.75	

Appendix D: Prism Data

Table D-1. CMU prism data.

CMU SAMPLE NUMBER	CONSTRUCTION DATE	TEST DATE	FRP OVERLAY TYPE	1st CRACK (kips)	PEAK LOAD (kips)	*fm* (psi)	MORTAR CUBE *fc* (psi)
1	12/22/97	1/22/98	None	81	116	2363	1577
2	12/22/97	4/23/98	Glass-Vinyl Ester	69	121.4	2473	1319
3	12/22/97	4/23/98	Glass-Vinyl Ester	65	114.6	2335	1319
4	12/22/97	4/23/98	Glass-Epoxy	55	111.4	2270	1659
5	12/22/97	1/22/98	None	64	108.8	2217	1659
6	12/23/97	1/22/98	None	77	123	2506	1806
7	12/23/97	6/4/98	Glass Grid-Epoxy	59	110.2	2245	1803
8	12/23/97	6/4/98	Glass Grid-Epoxy	52	103.4	2107	1803
9	12/23/97	6/4/98	Glass Grid-Epoxy	?	110.6	2253	1803
10	12/23/97	4/23/98	Glass-Vinyl Ester	50	94	1915	1803
11	12/23/97	4/23/98	Carbon-Epoxy	61	109	2221	1861
12	12/26/97	4/23/98	Carbon-Epoxy	59	100.4	2045	2220
13	12/26/97	4/23/98	Carbon-Epoxy	50	111.4	2270	2220
14	12/26/97	4/23/98	Glass-Epoxy	60	111.6	2274	2220
15	12/26/97	4/23/98	Glass-Epoxy	?	109.4	2229	2220

Table D-2. Brick prism data.

BRICK SAMPLE NUMBER	CONSTRUCTION DATE	TEST DATE	FRP OVERLAY TYPE	1st CRACK (kips)	PEAK LOAD (kips)	f_m (psi)	MORTAR CUBE f_c (psi)
1	12/23/97	1/22/98	None	25	53.5	2219	1860
2	12/23/97	1/22/98	None	30.5	53	2198	1860
3	12/23/97	1/22/98	None	35.5	50	2074	1860
4	12/26/97	6/4/98	Glass Grid-Epoxy	45	72.5	3007	2195
5	12/29/97	6/4/98	Glass Grid-Epoxy	46.5	66.6	2763	1991
6	12/29/97	4/23/98	Carbon-Epoxy	41	63.8	2646	2363
7	12/29/97	4/23/98	Carbon-Epoxy	44	68.7	2850	2090
8	12/30/97	4/23/98	Glass-Vinyl Ester	50.5	72.3	2999	2533
9	12/30/97	6/4/98	Glass Grid-Epoxy	43	56.2	2331	2159
10	12/31/97	4/23/98	Glass-Epoxy	41	58	2406	2337
11	12/31/97	4/23/98	Glass-Vinyl Ester	41	67.5	2800	2233
12	1/2/98	4/23/98	Glass-Epoxy	43	78.8	3269	2732
13	1/2/98	4/23/98	Glass-Epoxy	52	78.4	3252	2233
14	1/5/98	4/23/98	Carbon-Epoxy	48	65.5	2717	2539
15	1/5/98	4/23/98	Glass-Vinyl Ester	54	86.6	3592	2075

Appendix E: Triplet Test Data

Table E-1. Triplet test data.

SAMPLE NUMBER	CONSTRUCTION DATE	FRP OVERLAY TYPE	NUMBER FRP PLIES	FRP WIDTH (in.)	TEST DATE	PEAK LOAD (lb)	AVERAGE PEAK LOAD (lb)
1	12/26/97	None	0	0	1/22/98	1771.2	
2	12/26/97	None	0	0	1/22/98	*	
3	12/26/97	None	0	0	1/22/98	2788.3	2280.3
4	12/26/97	None	0	0	2/5/98	3302.4	
5	12/26/97	None	0	0	2/5/98	988.8	
6	12/26/97	Glass-Epoxy	1	6	8/17/98	12000.0	
7	12/29/97	Glass-Epoxy	1	6	8/17/98	9696.0	13311.0
8	12/29/97	Glass-Epoxy	1	6	8/17/98	8241.0	
9	12/29/97	None	0	0	1/22/98	2551.0	
10	12/29/97	Glass-Epoxy	1	5	8/17/98	8745.0	
11	12/29/97	Glass-Epoxy	1	5	8/17/98	9436.0	9275.3
12	12/29/97	Glass-Epoxy	1	5	8/17/98	9645.0	
13	12/30/97	Glass-Epoxy	1	4	8/17/98	8851.0	
14	12/30/97	Glass-Epoxy	1	4	8/18/98	8396.0	8521.7
15	12/30/97	Glass-Epoxy	1	4	8/17/98	8318.0	
16	12/30/97	Glass-Epoxy	1	3	8/17/98	7782.0	
17	12/30/97	Glass-Epoxy	1	3	8/17/98	5706.0	6738.3
18	12/30/97	Glass-Epoxy	1	3	8/17/98	6727.0	
19	12/30/97	Glass-Epoxy	1	2	8/17/98	5904.0	
20	12/30/97	Glass-Epoxy	1	2	8/18/98	5306.0	5556.3
21	12/30/97	Glass-Epoxy	1	2	8/17/98	5459.0	
22	12/30/97	Glass-Epoxy	1	1	8/17/98	4247.0	
23	12/30/97	Glass-Epoxy	1	1	8/17/98	4319.0	4187.0
24	12/31/97	Glass-Epoxy	1	1	8/17/98	3995.0	
25	12/31/97	Carbon-Epoxy	1	2	8/17/98	7323.0	
26	12/31/97	Carbon-Epoxy	1	2	8/17/98	8097.0	7958.7
27	12/31/97	Carbon-Epoxy	1	2	8/17/98	8456.0	
28	12/31/97	Carbon-Epoxy	1	1	8/17/98	5400.0	
29	12/31/97	Carbon-Epoxy	1	1	8/18/98	5996.0	5464.0
30	12/31/97	Carbon-Epoxy	1	1	8/17/98	4996.0	

SAMPLE NUMBER	CONSTRUCTION DATE	FRP OVERLAY TYPE	NUMBER FRP PLIES	FRP WIDTH (in.)	TEST DATE	PEAK LOAD (lb)	AVERAGE PEAK LOAD (lb)
31	12/31/97	Glass-Epoxy	3	6	12/3/98	19600.0	
32	12/31/97	Glass-Epoxy	3	6	11/20/98	*	19150.0
33	12/31/97	Glass-Epoxy	3	6	12/3/98	18700.0	
34	12/31/97	Carbon-Epoxy	1	6	12/3/98	13800.0	
35	12/31/97	Carbon-Epoxy	1	6	12/3/98	13600.0	13666.7
36	12/31/97	Carbon-Epoxy	1	6	12/3/98	13600.0	
37	1/2/98	Glass-Epoxy	2	6	11/20/98	16900.0	
38	1/2/98	Glass-Epoxy	2	6	12/3/98	15100.0	15366.7
39	1/2/98	Glass-Epoxy	2	6	12/3/98	14100.0	
40	1/2/98	Carbon-Epoxy	1	5	1/22/98	12000.0	
41	1/2/98	Carbon-Epoxy	1	5	1/22/98	12900.0	11833.3
42	1/2/98	Carbon-Epoxy	1	5	1/22/98	10600.0	
43	1/2/98	Carbon-Epoxy	1	4	12/3/98	16200.0	
44	1/2/98	Carbon-Epoxy	1	4	12/3/98	15300.0	13691.0
45	1/2/98	Carbon-Epoxy	1	4	8/17/98	9573.0	
46	1/2/98	Carbon-Epoxy	1	3	8/17/98	9663.0	
47	1/2/98	Carbon-Epoxy	1	3	8/18/98	9975.0	10546.0
48	1/2/98	Carbon-Epoxy	1	3	11/20/98	12000.0	
49	1/5/98	Carbon-Epoxy	2	6	12/3/98	17400.0	
50	1/5/98	Carbon-Epoxy	2	6	12/3/98	18500.0	16566.7
51	1/5/98	Carbon-Epoxy	2	6	12/3/98	13800.0	

* Specimen destroyed by hydraulic spike in test machine and data not acquired.

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10
5/00

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE June 2000

2. REPORT TYPE Final

3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE
Performance Testing of Fiber-Reinforced Polymer Composite Overlays for Seismic Rehabilitation of Unreinforced Masonry Walls

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62784

6. AUTHOR(S)
Orange S. Marshall, Steven C. Sweeney, Jonathan C. Trovillion

5d. PROJECT NUMBER
AT41

5e. TASK NUMBER

5f. WORK UNIT NUMBER
FL-003

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Construction Engineering Research Laboratory (CERL)
P.O. Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CERL TR-00-18

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers Headquarters
Military Programs Office
20 Massachusetts Ave
Washington DC, 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)
CEMP-ET

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

14. ABSTRACT

A large portion of the Army's facility inventory incorporates load-bearing unreinformced masonry (URM) walls. Because this type of structural system has been shown to perform poorly in past earthquakes, structural upgrade technology is needed to protect facility occupants and mission-critical operations during and after seismic activity. This research investigated procedures for strengthening masonry walls using readily available advanced composite materials systems.

New 4 x 4 ft wall panels of double-wythe brick or concrete masonry unit (CMU) construction were reinforced with FRP composite materials applied to one face. These wall specimens were tested to failure on a million-pound load test machine at the U.S. Army Construction Engineering Research Laboratory (CERL). Load tests also were performed on FRP-reinformced standard masonry prisms, and shear tests were conducted on different widths and thicknesses of FRP composite applied across the mortar joints of brick triplets.

FRP composites show great potential for seismic hardening of URM walls. Triplet tests demonstrated consistent strengthening of the mortar joints as a function of the width and thickness of the FRP composite overlay.

15. SUBJECT TERMS
composite materials, fiber reinforced polymer (FRP), masonry, seismic strengthening, structural engineering, walls

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	SAR	59	Orange S. Marshall
					19b. TELEPHONE NUMBER (include area code)